Magnet laboratory facilities worldwide – an update

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Abstract

Generation of high magnetic fields for materials research and fundamental science requires specialized laboratories of considerable size. In this paper we provide an overview of facilities available worldwide for very strong static and pulsed magnetic fields.

1. Introduction

The magnetic field, like temperature and pressure, is one of the basic parameters that are used to change the physical state of matter [1]. Increasing the range of any of these parameters has invariably led to new discoveries and contributed much fundamental knowledge to the understanding of the solid state. This is reflected in the papers at this conference, and in the excellent reviews that have been published in recent years [2–4]. This paper is focused on the facilities where very high magnetic fields are available for research in all domains of solid state physics and materials research. Modern laboratory magnets involve sophisticated technology and major investments, as witnessed by the large static magnetic field facilities that have been established in Europe, Japan and the USA, and by the developments in materials technology that will enable the design of pulsed magnets that soon may reach the 100 T limit.

The design of stronger laboratory magnets has been pursued at all times since the discovery of electromagnetism. Originally these were iron magnets that worked with modest power, and in fact iron-yoke electromagnets still remain a viable option for moderately strong laboratory magnets until today. Noteworthy is the extremely large (120 000 kg) but versatile electromagnet that was constructed around 1924 by Aimé Cotton at the laboratory of the Académie de Sciences in Bellevue, Paris: with some 100 kW of power, this magnet could generate up to 7 T or so, depending on the choice of pole-tips and pole-gap [5]. It is fair to say that the Labora-

toire Aimé Cotton was the first large facility for research in high magnetic fields.

Fig. 1 shows the progress made in this century with magnet coils of different technologies. Let us first review the development of resistive magnets (□). In 1914 two frenchmen, Deslandres and Péro, had demonstrated the capabilities of air core solenoids: with 350 kW and a water-cooled coil manufactured from silver strips they were able to generate 5 T in 20 mm bore [6]. Francis Bitter at M.I.T., realising that airgap solenoids would be more efficient for fields in excess of the saturation field of iron yoke electromagnets, produced in 1936 a record breaking field of 10 T in a 25 mm bore solenoid assembled from copper disks, with a power consumption of 1 700 kW [7]. His revolutionary design of the ‘Bitter magnet’ is still in use today.

Early work included also the work of Giauque at the University of California in Berkeley, and in the years after World War II the research at the University of Oxford and the Naval Research Laboratory in Washington DC. It was in this last laboratory in 1962 with a somewhat larger power source that the Bitter concept was pushed to 15.2 T. Bitter’s installation remained in operation until, at M.I.T. in 1960, the new National Magnet Laboratory was established. At the time many people realised that the requirements for power and cooling when operating high-field coils were so large that continuous high magnetic fields could only be realised in dedicated laboratories with the appropriate infrastructure, and the establishment of the new Magnet Laboratory at M.I.T. marks the era of installations with power sources of typically 10 MW (see Fig. 1). It was also soon

Fig. 1. Progress in generating static high magnetic fields. $\diamond$: superconducting magnets; $\square$: resistive, water-cooled magnets; $\triangle$: hybrid magnet systems, and ∇ : their superconducting background coils (open symbols ≤ 10 MW, filled symbols > 10 MW, ? : soon to be demonstrated).

realised that magnet designs with nested coils were necessary, because at very high magnetic field strengths the maximum allowed current density in the innermost parts of the magnet coil would be stress limited rather than power limited. In Oxford, in 1964, Wood was the first to use the polyhelix concept [8]. This concept was pushed very successfully in Grenoble, leading in 1982 to a record field of 25 T in 50 mm bore with a 10 MW polyhelix coil [9]. Now that installations are emerging with power and cooling in the 20 MW range, we see the development of resistive coils with maximum fields that will break the 30 tesla barrier.

In 1966, Wood and Montgomery proposed the concept of the hybrid magnet ($\triangle$) where the background field of a large size superconducting coil (∇) around the resistive, water-cooled magnet allows to generate much higher fields in an economical way [10]. The Francis Bitter National Magnet Laboratory was the first to build such a system and in 1974 generated 20 T [11]. A smaller 16 T hybrid magnet was constructed at the Clarendon Laboratory in Oxford and has been in service for 15 years since 1975. In Table 1 an overview is given of hybrid magnets installed and under construction, ordered according to the maximum field. There are only four laboratories worldwide with magnets generating more than 30 tesla, and with 10 MW power plants, hybrid magnets have surpassed the 35 T threshold [12].

We are now witnessing the installation of 20 MW power supplies in many old and new high-field laboratories alike, and with these more powerful sources static fields in the 40 T range are coming within reach: a 40 T system built for the Tsukuba Magnet Laboratories will be coming into operation early in 1995 [13], and a 45 T system is being constructed for the National High Magnetic Field Laboratory in Tallahassee, Florida. It is evident that a new step has been made to field strengths in a large window of opportunity

for experiments well above the range conveniently accessible with state-of-the-art superconducting laboratory magnets ($\diamond$).

Over the last twenty-five years there has been a great advance in superconducting technology, and commercially produced laboratory magnets up to 20 T are finding their way into physics and chemistry laboratories. This has led to a spread and decentralisation of high-magnetic-field research (and the growing number of high-magnetic-field conferences and an increasing audience at these meetings bears witness to this fact), while there also is a vivid demand for easy-to-use high-power water-cooled resistive magnets, and the very strong fields that can only be produced by the hybrid magnet systems at the large user-oriented high-magnetic-field facilities.

The problem of power consumption and cooling was circumvented by the development of pulsed magnets that rely on the heat capacity of the (usually) precooled coil. This was pioneered and brought to a first peak by P. Kapitza [14] who used an alternator as the pulsed energy source. Later on, several small capacitor-driven pulsed magnets were set up in different laboratories, typically with fields below 50 T and pulse duration of the order 10 ms. The peak field of these magnets is limited by the mechanical strength of the coils. A breakthrough was achieved by S. Foner [15] who used newly developed high-tech materials to generate for the first time a pulsed field of almost 70 T. This inspired other research groups to develop pulsed magnets for fields in excess of 70 T, and the optimism that was generated by these successful developments is the basis for very ambitious plans to develop a nondestructive 100 T magnet.

The megagauss ($= 100$ T) limit was breached around 1960 with two different methods: magnetic flux compression by means of high explosives and the discharge of a fast capacitor bank into a small single turn coil. Shortly afterwards it was shown that electromagnetically driven flux compression has the potential to generate extremely high fields. These magnets rely on inertial confinement; the destruction is accompanied by shock waves which limit the pulse duration in devices of practical size to the microsecond range. Experimentation under these extreme conditions is difficult and it took many years until these magnets were used for experiments. Nowadays both explosive-driven and electromagnetic devices are used for a variety of experiments, even at cryogenic temperatures.

There have been several surveys on magnet laboratory facilities. The first extensive survey, including a brief history, was given by Herlach [16]. Later surveys and updates were given at the symposia on High Field Magnetism and at the TODAI symposium [17–19]. The present paper is an attempt to provide a complete update, inspired by recent advances in this field and interesting prospects for the future, in particular the plans to establish a European High Field Facility.

Table 1
Hybrid magnet systems, installed and under construction

Laboratory	$B_{S/C}/\text{bore}$	$B_{\text{max}}/\text{bore}$	
NHMFL, Tallahassee (FL)	15 T @ 630 mm	45 T @ 32 mm	Under construction
NRIM, Tsukuba	15 T @ 400 mm	40 T @ 30 mm	About to be tested
		35 T @ 50 mm	
FBNML, Cambridge (MA)	12.2 T @ 355 mm	35.2 T @ 32 mm	'Hybrid-III'
		23 T @ 144 mm	
	7 T @ 355 mm	31.8 T @ 32 mm	'Hybrid-II'
		27 T @ 51 mm	
HMFL, Grenoble	11.0 T @ 420 mm	31.4 T @ 50 mm	
IMR, Sendai	12 T @ 360 mm	31.1 T @ 32 mm	'HM-1'
		28.1 T @ 52 mm	
		23.6 T @ 52 mm	'HM-2'
HFML, Nijmegen	10.8 T @ 355 mm	30.4 T @ 32 mm	'Nijmegen-II'
	8 T @ 355 mm	25.0 T @ 53 mm	'Nijmegen-I'
Kurchatov Institute, Moscow	6.3 T @ 300 mm	24.6 T @ 28 mm	
Clarendon Laboratory, Oxford	10 T @ 243 mm	24 T @ 30 mm	Under construction
Academia Sinica, Hefei	7.5 T @ 266 mm	20.2 T @ 32 mm	

All high magnetic field laboratories known to the authors have been contacted with a standardized set of questions, and the material presented in this paper is taken from the responses. However, references regarding listed facilities that are contained in previous reviews have not been exhaustively repeated.

2. Water-cooled resistive, and hybrid magnets

Because of the enormous requirements for electrical power and cooling capacity, high magnetic field facilities tend to be centralised and specialised laboratories, often being run in a user-oriented mode. In Table 2 an overview is given of the facilities and their general characteristics, ordered according to the maximum magnetic field strength that they can maintain. In the following (where we have chosen the year of establishment of the facility as the key) for each of these laboratories some detailed information is provided.

Oxford: High Magnetic Field Facilities

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The high magnetic field facilities at the Clarendon Laboratory of the University of Oxford date back to 1946. Although the laboratory still maintains one magnet station, a 24 tesla hybrid magnet [20], and superconducting magnets,

it is concentrating resources on pulsed magnet operation since 1991.

Characteristics: The power source is a 2 MW motor generator which can deliver 500 A @ 400 V with a 10^{-5} current ripple. For cooling, 150 m³/h of water is pressed through the resistive part of the hybrid magnet at a pressure of 1000 kPa. The cooling is water to air fan assisted, with a 80 m³ reservoir (corresponding to about 4 MWh). The superconducting section of the hybrid magnet is a 243 mm warm bore superfluid cooled NbTi coil giving a 10 T background field, which combined with a resistive insert will generate 24 T in 30 mm bore (or 20 T in 50 mm bore). This magnet replaces a 20 T system that was in operation until 1990, and it is still in the process of installation.

Cambridge: Francis Bitter National Magnet Laboratory at M.I.T.

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The facility was established in 1960 and has been supported by the National Science Foundation since 1970 [12]. It was a continuation of the pioneering work of Francis Bitter at M.I.T., and the laboratory has held a leading position in magnet technology and research in high magnetic fields for many years. The FBNML was successful in designing and constructing the first hybrid magnet system, and Hybrid-III with its peak field of 35.2 T is presently the strongest hybrid magnet in operation worldwide.

Table 2

Summary of facilities for high static magnetic fields

Facility	Founded (year)	Power	Cooling	# Stations	$B_{\max}$ (resistive)	$B_{\max}$ (hybrid)
Tsukuba, Japan	1988	15 MW	Chillers & cooling tower	1 (5)	25T@30 mm	40T@30 mm
Cambridge (MA), USA	1960	10 MW	Heat exchange with river	25	24T@32 mm	35.2T@32 mm
Grenoble, France	1970	2×12 MW	Heat exchange with river	6	25T@50 mm	31.4T@50 mm
Sendai, Japan	1981	8 MW	Chillers & cooling tower	4	17T@32 mm	31.1T@32 mm
Nijmegen, Netherlands	1972	6 MW	Chilled 0°C buffer, 20 MWh	5	20T@32 mm	30.4T@32 mm
Tallahassee (FL), USA	1990	34 (40) MW	Chillers & cooling tower	3 (..)	27T@32 mm	Under construction
Oxford, Great Britain	1972	2 MW	80 m ³ reservoir/ventilator	1		24T@30 mm
Hefei, China	1984	10 MW	5000 m ³ pool/chiller	4	13T@32 mm	20.2T@32 mm
Wroclaw, Poland	1968	5.5 MW	800 m ³ pool/splasher	3	19T@25 mm	–
Braunschweig, Germany	1972	5.6 MW	Cooling tower 7.6 MW	4	18.2T@32.4 mm	–
Krasnoyarsk, Russia	1990	7.5 MW	Heat exchange with mains	2	15T@36 mm	–

Characteristics: The available power is 10 MW delivered by two motor generators (41 kA @ 230 V, overload capability to 12 MW for 15 minutes), and the stability and ripple is 10^{-3} , 5×10^{-5} with stabilizer. The two generators can either deliver 5 MW each to two different magnets, or the combined power to one high-power coil. About 300–450 m³/h of purified water is pressed through the magnets (plant capacity 900 m³/h) at 1000–1400 kPa, and cooled down by heat exchange to water from the nearby Charles river. The facility is running 14 hours per day for five days per week.

There is a large variety of magnets installed on 25 different magnet stations. The strongest magnets are two fully operational hybrid magnet systems, a 35.2 T, 33 mm bore hybrid (Hybrid III) in operation since 1993, and a 31.8 T, 33 mm bore hybrid (Hybrid II) in service since 1981. There are also wider bore inserts for the hybrid systems, with consequently lower field strength, and even higher fields (+3.5 T) can be achieved in a restricted volume using ferromagnetic holmium pole pieces. The purely resistive magnets range from 24 T, 32 mm bore to 7.5 T, 248 mm bore solenoids, while there are a number of coils providing radial access (horizontal and vertical, from 20 mm to 51 mm), e.g. a 32 mm vertical radial access 15 T coil. There are also a number of 5 MW magnets in operation (typically with up to 19.5 T in 32 mm bore) with the advantage that any two of them can be run simultaneously.

Moscow: Kurchatov Institute

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At the Kurchatov Institute there is a 25 T hybrid magnet system which was first successfully operated in 1975 [21]. It is a 6.3 T, 300 mm bore superconducting magnet that with

a 5.6 MW resistive insert coil generated 24.6 T. There were plans to upgrade the superconducting magnet to 12.5 T, but we have received no recent information on the status of this laboratory.

Wroclaw: International Laboratory of High Magnetic Fields and Low Temperatures

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The laboratory started operation in 1968 as a collaboration of the Academies of Science of Bulgaria, the German Democratic Republic, Poland and the Soviet Socialist Republics [22]. Since the reunification of Germany in 1990, the ordinary members (i.e. the Academies of Sciences of Bulgaria, Poland and Russia) contribute to the costs of the laboratory while there are a number of associate members with the right to perform measurements in the laboratory. The International Laboratory is under reconstruction, and started a development programme for a 60 T quasi-stationary magnet in collaboration with the Russian Academy of Sciences.

Characteristics: The motor generator power supply can deliver 5.5 MW to the magnets (11 kA @ 580 V, overload capability 6 MW for 10 minutes), and 180 m³/h purified water, cooled by heat exchangers to a 800 m³ pool with splashers, is run through the magnets at a pressure up to 1800 kPa. Three resistive magnets are installed, the strongest is a 3-section coil generating 20.2 T in 25 mm bore with 6 MW.

Grenoble: High Magnetic Field Laboratory

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The laboratory is a collaborative effort of the the Conseil National de Recherche Scientifique (France) and the Max Planck Institut für Festkörperforschung (Germany) who in 1972 initiated a joint agreement for the enlargement (to 10 MW) and common exploitation of the Service National des Champs Intenses in Grenoble [23,24]. It was in this laboratory that in 1980 von Klitzing made his discovery of the Quantum Hall effect [25] that deserved him the Nobel prize. Noteworthy is the implementation of the polyhelix technology, that allowed Schneider-Muntau to generate a record 25 tesla in 50 mm bore [9]. A similar inner coil was also employed in the Grenoble hybrid magnet to obtain 31.4 T in 50 mm bore. In 1991 the laboratory underwent a major upgrading with a doubling of its power and cooling plants.

Characteristics: The 20 MW power supply consists of 4 units 15 kA @ 340 V each (overload capability 16.5 kA @ 370 V); each unit is a thyristor regulated 24 pulse system with passive and active filtering, and the resulting current ripple and stability is better than 5×10^{-5} . Cooling water is delivered to the magnets at a nominal pressure of 2700 kPa up to $2 \times 400 \text{ m}^3/\text{h}$ by 1 or 2 variable speed centrifugal pumps. A secondary open loop of river water removes the dissipated heat through a heat exchanger [24]. The laboratory is available for experiments around the clock, and magnets are operated typically more than 4300 hour each year.

There are 9 magnet stations, one of these houses the 30 T, 50 mm bore hybrid magnet system. The coils installed range from a 25 T, 50 mm bore polyhelix to large-bore (6.5 T, 284 mm bore), and highly homogeneous (19 T, 50 mm bore) coils, and a coil with radial access. Higher power coils (i.e. more than 10 MW) are under construction.

Braunschweig: *Hochmagnetfeldanlage der TU Braunschweig*

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The laboratory was established in 1972, it provides research opportunities for faculty members and students, and the facilities are open to guest scientists [26].

Characteristics: A unique solid-state power system provides a very low field ripple and very small long-term drift of better than 1.5×10^{-6} . The available power is 5.6 MW (21 kA @ 275 V), and the water flow through the magnets is $350 \text{ m}^3/\text{h}$ @ 700 kPa (usual, maximum possible 2500 kPa) while the cooling is provided real-time by a 7.6 MW cooling tower.

The installation runs 4 Bitter type magnets, 16.2 T with 53.4 mm bore to 18.2 T with 32.4 mm bore.

Nijmegen: *Nijmegen High Field Magnet Laboratory*
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The laboratory started full operation in 1976, and is run by the University of Nijmegen [27,28]. The guest-user program also benefits from funding by the European Union and the Dutch F.O.M. The laboratory collaborates very closely with the pulsed field facility at the van der Waals–Zeeman Laboratory of the University of Amsterdam in the “Amsterdam–Nijmegen Magnet Laboratory”.

Characteristics: The power supply can deliver 6 MW (20 kA @ 300 V) to the magnets (the 100% overload capability of the power supply has never been used); the current/field ripple is 2×10^{-5} , predominantly at 300 Hz. A maximum flow of $400 \text{ m}^3/\text{h}$ water is pressed through the magnet coils at a pressure of up to 2300 kPa. Cooling capacity to near 10 MW is obtained through heat exchange with a reservoir of ice and water at 0°C in a 450 m^3 basin. The cold mass, that can absorb $\approx 20 \text{ MWh}$, is cooled by chillers that give off their heat to ground water. During normal working hours operation is at reduced power; power can be used with no restriction after 19:00 h and on weekends. The magnet-plant operates typically 1500 hours per year.

The laboratory has two fully operational hybrid magnet systems (constructed by FBNML at M.I.T.), Nijmegen-II, in operation since 1985, generates 30.4 T in 32 mm bore with a radially-cooled insert coil in the 10.8 T background field of a superfluid cooled NbTi coil, and Nijmegen-I, in operation since 1978, generates 25.0 T in 53 mm bore with a 8 T, NbTi outer coil. In the three other stations served, Bitter-type resistive magnets are installed (20 T @ 32 mm, and 15 T @ 60 mm).

Sendai: *High Field Laboratory for Superconducting Materials*

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This laboratory was established in 1981 in order to provide research facilities for the development of superconducting materials; it is an upgrade of an earlier 3 MW plant, dating back to 1957, that was used to energise water-cooled Bitter magnets and that had become obsolete in the light of the development of stronger superconducting magnets. The laboratory has several hybrid magnet systems and is also active in the field of pulsed magnets [29,30].

Characteristics: The available electric power is 8 MW (23 kA @ 350 V) with a current ripple of 10^{-4} ; $350 \text{ m}^3/\text{h}$ of

water is circulated through the resistive coils at a pressure of 2000 kPa from 160 m³ tanks, and this circuit is cooled by two combinations of a chiller with a cooling tower (3 MW each). In HM-1 a 360 mm bore outer superconducting magnet (Nb₃Sn/NbTi) generates a background field of 12 T, with a 32 mm bore polyhelix insert a maximum field of 31.1 T can be generated (or 28.1 T with a 52 mm bore polyhelix insert). HM-2, with an outer, 360 mm bore, 8 T NbTi superconducting magnet, generates 23.6 T with a 52 mm bore Bitter coil. On three more magnet stations resistive magnets can be found: a 17 T, 32 mm bore Bitter/polyhelix coil, and wide-bore magnets such as a 15 T, 82 mm bore Bitter coil.

Hefei: High Magnetic Field Laboratory

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The high magnetic field laboratory was established in 1983, when facilities originally built for fusion research were made available. There were serious difficulties to realise the investments in the 4 MW power supply, and in 1990 the redundant 10 MW power supply of the Grenoble High Magnetic Field Laboratory was donated and transferred to this institute. In 1992, using the reassembled power supply, the hybrid magnet was successfully tested to its design field of 20.2 T (with 3.0 MW in the resistive coil) [31]. Also since 1992, the laboratory is an open facility for scientists from all over the country.

Characteristics: The available power is 10 MW (30 kA @ 335 V) and with a 12 pulse SCR circuit, and active and passive filtering, a high stability of up to 1×10^{-5} is obtained. Water flow through the magnets is 150 m³/h @ 2000 kPa; the cooling is provided by a cooling pond of 5000 m³ and an optional chiller helps to maintain inlet temperatures below 20°C. The hybrid magnet features a 7.5 T, 266 mm bore NbTi coil and a 13 T, 32 mm bore resistive insert coil. There are three resistive magnets, a 13 T, 32 mm bore coil designed at the laboratory, and two 4 MW magnets with larger bore from Grenoble (15 T with 50 mm bore).

Tsukuba: Tsukuba Magnet Laboratories

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This laboratory has been established recently and will start full operation in 1995 [13,32]. Apart from the activities in generation of high magnetic fields there is a big effort in the development of strong conductors (Cu–Ag alloy), superconducting magnets and NMR. An eye catching achievement was the generation of 21.8 T by combining more conven-

tional superconducting magnets with a Bi-2212 superconducting insert coil. The laboratory also has programmes in developing and using pulsed field coils.

Characteristics: The available electric power is 15 MW (35 kA @ 430 V), with a current ripple of 1×10^{-4} . Cooling water can be provided to 600 m³/h at 1500 kPa, and cooling is provided by a combination of chillers with cooling towers with a cold buffer corresponding to 1.8 MWh. The 40 T hybrid magnet is expected to soon become fully operational: the NbTi/Nb₃Sn, 400 mm room temperature bore, superconducting magnet was successfully tested to 14 T, and the entire hybrid magnet with polyhelix resistive inserts of varying bore will be tested to design field early in 1995.

Tallahassee: National High Magnetic Field Laboratory

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The National High Magnetic Field Laboratory was established in 1990, and is a collaboration between Florida State University, the University of Florida and Los Alamos National Laboratory, and also receives funding from the National Science Foundation (NSF) and the State of Florida. The laboratory has the most powerful infrastructure to energize resistive magnet coils found anywhere in the world (up to 34 MW, and even 40 MW in overload!). Apart from the programme of research in static high magnetic fields there is an extensive programme of NMR, both in research and in development of future high-field NMR magnets, and in ultra-low-temperatures. The first high-power resistive coils, of the poly-Bitter type and designed at the laboratory, have already been put into operation, and a 45 T hybrid magnet system is under construction [33–35]. The pulsed magnet programme of NHMFL is located at the Los Alamos National Laboratory.

Characteristics: The electric power is delivered by four 24-pulse thyristor bridge rectifying units, with passive and active filters. The power rating is 27 MW (4×17 kA @ 400 V), or 34 MW (4×17 kA @ 500 V), while there is an overload capability to 40 MW (4×20 kA @ 500 V) for one hour; current ripple and stability is almost 1×10^{-6} . A maximum flow of cooling water of 1500 m³/h can be pressed through the resistive coils using variable speed pumps, and at water pressures that can be set between 1000 and 4000 kPa; cooling is obtained through combinations of chillers with cooling towers (4 units, with a total capacity of 27 MW) with a cold buffer of 3800 m³ chilled water (corresponding to 56 MWh). At this date there are 3 magnet stations in operation, with among them the first 27 T, 32 mm bore coil designed in the laboratory. There is a development programme

for resistive magnets to well above 35 T [34]. The laboratory also has two 20 T superconducting research magnets for general use. In a joint effort the NHMFL and FBNML at MIT are developing a 45 T hybrid, featuring a novel design, 15 T, 630 mm room temperature bore, cable in conduit, superfluid cooled NbTi/Nb₃Sn superconducting magnet, and a 30 T, 32 mm bore radially cooled Bitter magnet as resistive insert. The laboratory operates daily from 7:00 to 23:30 h, with almost no restrictions.

Krasnoyarsk: *High Stationary Magnetic Fields Laboratory*

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A new installation was constructed in 1990–1992 [36], with resistive water-cooled magnets developed earlier in collaboration with the International Laboratory of High Magnetic Fields and Low Temperatures in Wrocław.

Characteristics: The available power is 7.5 MW (25 kA @ 300 V, overload capability to 30 kA, 9 MW, for up to 30 min) with a 12-pulse thyristor based supply, and the water flow through the magnets is 250 m³/h @ 1000 kPa, while the cooling water is cooled to about 10°C by heat-exchange with the main water supply. A 15 T, 36 mm bore, 5 MW Bitter magnet is operating, and a 24 T, 30 mm bore polyhelix magnet is being constructed.

3. Nondestructive pulsed magnets

The natural limit above which coils are inevitably destroyed by the Maxwell stress is situated around 100 T. At present, the highest fields that have been obtained without coil destruction are slightly above 70 T, and reliable coils for daily use generate about 60 T in a bore of less than 20 mm. The necessary high mechanical strength is obtained by either using high strength conductors (Cu–Nb or Cu–Ag microfilaments, Cu reinforced with a stainless steel jacket or with steel filaments, hardened copper, Glidcop or copper–beryllium). The pulse duration is only limited by the available energy and by the coil mass which has to absorb the heat generated in the pulse. Most pulsed field facilities use a capacitor bank as the energy source; the pulse shape is a damped sine wave distorted by the heating of the coil, and the decay is prolonged and exponential if a ‘crowbar’ (usually by means of diodes) is used. The effect of the crowbar can be adjusted if variable resistors are used in the crowbar circuit. Some large facilities use power from the mains (Amsterdam) or from a flywheel-generator (Los Alamos,

Princeton) with controlled rectification which allows to generate a variety of waveforms. Basic data from all facilities are compiled in Table 3; abbreviations used for the characteristics of the energy source (unless otherwise mentioned, a capacitor bank) are given in Table 4. Contact persons, addresses and special features for all these different laboratories are listed below.

Amsterdam: *Amsterdam High Magnetic Field Facility*

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The stimulus for setting up this unique installation was given by G.W. Rathenau in 1959. The coil was designed by R. Gersdorf and the facility became operational in 1964 [37]. A 40 T magnet has been in use since 1969 for nearly 100 000 pulses, about 10% of these at fields above 30 T. The power is directly taken from the 10 kV utility grid, controlled rectification by a 6-phase thyristor converter allows to generate a precisely controllable waveform. Two identical coils are in operation, one is precooled to 30 K by liquid neon and generates 40 T, the other is operated in liquid nitrogen and generates 30 T. The pulse shape can include a flat top of 60–100 ms duration, with a ripple of 10^{−4}, and all kinds of ramps and staircases. It is possible to obtain a free running exponential decay by means of a crowbar affected by an additional thyristor. Experiments are mainly concerned with magnetization, de Haas–van Alphen and magnetotransport measurements. A 60 T controlled waveform magnet has been funded and the design is in progress. This magnet will be energized by a motor-generator. The Amsterdam High Magnetic Field Facility collaborates very closely with the Nijmegen High Field Magnet Laboratory in the ‘Amsterdam–Nijmegen Magnet Laboratory’.

Beijing: *High Magnetic Field Laboratory*

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The High Magnetic Field Laboratory of the Chinese Academy of Sciences was established in 1988 [38]. The development of pulsed magnets in China is in step with that of other countries. Different types of strong wire have been developed with special emphasis on the insulation of the wire. Magnets are designed with constant current

Table 3
Magnet laboratories using nondestructive pulsed magnets

Laboratory location	W [MJ]	U [kV]	I [kA]	B [T]	Bore [mm]	t_r [ms]	$\int B dt$ [T s]	dB/dt [T/ms]	Cool [min]	Energy source
Amsterdam	3	1	9.4	40	22	250	17	0.2	100	UG T cw Cf
(1999:)	26	5	9.5	60	25	400	30	0.15–1.3	100	MG T cw Cf
Beijing	0.34	5		50	22	3.5		30	30	I
Berlin	0.05	2.5	30	50	10	2	0.16	62	10	T/I
(1994:)	0.4	10	60	60	20	6	0.5	15	45	T Cv pr
Braunschweig	0.4	2.5	1	27	12	5	0.2	9	7	T Cf
Bristol	0.13	5	130	60	10	3.5	0.73	20	40	T
	0.18	8								
Dublin	0.29	7.5	2	26	28	52	4	0.8	60	T Cf
Kobe	0.024	3	7.6	30	15	5	0.19	9.42	20	T/I
	0.1	10	22	20	40	0.5	0.013	62.8	2 sec	I
Leuven	1.2	5/10	100	60	17	6.5	0.5	14	45	To pr
Los Alamos	1.1	10	1000	60	14	7	0.61	12	45	I Cv
				50	24	7.5	0.61	10	45	
(1995:)	600	4/8	20	60	32	1100	36.2	0.31	≈45	MG T cw Cv pr
M.I.T.	0.21	4	150	65	13	3.4	0.31	36	20–25	I pr Cv
				60	20	4.1	0.35	26		
				55	22	4.5	0.35	20		
Moscow Kurchatov	0.18	5	20	55	15	6		14	18	T
Moscow State Univ.	0.03	1	8	32	13	3	0.25	15	10	T Cf
Murray Hill	0.52	12	20	65	10	5	2	20	25	T Cv pr
Osaka	1.5	20	560	70	20	0.2	0.018	300	30	SG Cf
				50	60	0.2	0.013	210	30	
				40	20	10	0.509	3	40	
Oxford	0.8	7	20	50	20	5	0.36	9	30	T I Cv pr
Parma	0.03	5	250	34	22	0.6	0.025	89	15	I Cf
(under construction:)	1	3	360	> 60	22–32	5–50	4	19	60	T Cv pr
Porto	0.6	7.3	2.1	25	30	100	11.5	2.5	30	T Cf
Princeton	72	9	22	64	20	1500	62	1	60	MG cw
Sendai	0.1	5	9	40	12	4	0.2	36	15	I
St. Petersburg Ioffe	0.075	5	15	35–40	22	2–5	1.5	30	10	T Cv pr
St. Petersburg TU	0.8	5	100	10	246	10		1.5		T
Sydney	0.8	7	60	60	22	10	0.8	20	30	T Cv pr
				30	30	80	8	0.7	60	
Tokyo	0.3	5/10	100	55	16	6	0.32	18	30	I Cv pr
	0.2	5	50							T pr
	0.11	4	100							I pr
Toulouse	1.25	10	4	61	11	40		2.4	45	To Ct
				42	26	90	23	0.7		
(1995:)	12	22	4	45	40	1000	120	0.07		To Cv pr
				60	30	200	31	0.47		
Tsukuba	0.125	5	50	73	10	1.9	0.21	66	60	I Cf pr
	1.6	5	500		20	25	2.5	70	60	I Cv
Vienna	0.075	2.5	100	43	25	2				T/I Cf
Worcester	0.35	5	50	55	18	11	0.93	8.9	50	T Cv
Wroclaw	0.07	3	24	47	10–22	4	0.19	1	25	T
Zaragoza	1.2	7.1	2.6	31	30	150	15	0.31	60	T Cf

density and with external reinforcement. Experiments are concerned with magnetic transitions and anisotropy, and with magnetophonon resonances.

Berlin: *Humboldt Universität*

Prof. M. von Ortenberg, Lehrstuhl Magnetotransport
Fachbereich Physik, Humboldt Universität

Invalidenstrasse 110, D-10115 Berlin (Germany)

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This new laboratory is in the first place dedicated to mega-gauss fields (see below), but it includes a state-of-the-art installation for nondestructive fields up to 70 T. The coils are designed and made at Leuven, partially in cooperation with M. Motokawa (ice coils [39]). Pioneering work has been done in the field of electrical diagnostics for sensitive magnetotransport experiments with the development of fast analog and digital lock-in techniques [40]. The facility includes optical instrumentation for the 7.5 mm to 10 μ m range with an optically pumped FIR laser and a continuously tunable carcinotron spectrometer.

Braunschweig: *Technische Universität Braunschweig*

Dr. D. Schneider, Institut für Technische Physik

Technische Universität Braunschweig

Mendelssohnstrasse 2, D-38106 Braunschweig (Germany)

Fax: +49-531 3915504

This laboratory was established in 1967 with an 11 T magnet. It is equipped for magnetoresistance measurements.

Bristol: *H.H. Wills Physics Laboratory*

Prof. M. Springford, H.H. Wills Physics Laboratory

University of Bristol

Tyndall Avenue, Bristol BS8 1TL (UK)

Fax: +44-272 255624

E-mail: mspringford@bristol.ac.uk

Pulsed magnets were installed in this laboratory after 1988, together with superconducting magnets, ^3He and dilution refrigerators (one top-loading for 20 mK and one for 0.8 mK at 19 T). Coils for the pulsed magnet were made by cooperation at Oxford and Leuven. An original computer-

ized system for monitoring the coils and for data recording was developed. Research is focused primarily on heavy fermion compounds, superconductors and mesoscopic systems.

Dublin: *Trinity College*

Prof. J.M.D. Coey, Trinity College

University of Dublin, Dublin 2 (Ireland)

Fax: +353-1 6711759

E-mail: jcoey@vax1.tcd.ie

This pulsed field facility is used as an auxiliary instrument in a laboratory that is dedicated to the study of magnetic materials.

Kobe: *Kobe University*

Dr. H. Ohta, Department of Physics

Kobe University, 1-1 Rokkodai, Nada, Kobe 657 (Japan)

Fax: +81-78 8030722

The magnet laboratory at Kobe University was set up in 1986 by M. Motokawa who developed pulsed magnets impregnated with water-ice instead of epoxy [41]. This facility is mainly used for submillimetre ESR, using Gunn oscillators, backward travelling wave tubes and an optically pumped FIR laser.

A second facility was set up in 1989 at the particle accelerator KEK (Tsukuba) for measurements with neutrons and muons; this is unique in that it provides repetitive pulses in 2 second intervals [42]. Contact person for this facility is M. Motokawa, now at Sendai (see below).

Leuven: *Katholieke Universiteit Leuven*

Prof. F. Herlach, Katholieke Universiteit Leuven

Celestijnenlaan 200 D, B-3001 Leuven (Belgium)

Fax: +32-16 327983

E-mail: fherlach@cc3.kuleuven.ac.be

The Leuven group has developed a new type of pulsed magnet with optimised reinforcement by fibre composites, resulting in record fields above 70 T with soft copper wire [43]. Still higher fields were obtained in cooperation with the Tsukuba group, using wire with Cu-Ag micro-filaments. Leuven is now coordinating the EC-sponsored EUROMAGTECH network (including Amsterdam, Grenoble, Oxford and Toulouse) for the development of strong conductor materials and associated coil designs. The experimental facility includes ^3He refrigerators (one built in cooperation with C. Agosta at Clark University), an optically pumped FIR laser and sensitive instrumentation for magnetotransport and magnetization experiments.

Table 4

Abbreviations describing pulsed energy sources

T	Thyristor (SCR)
To	Thyristor, optically triggered
I	Ignitron
SG	Spark gap
RG	Rail gap
Cf	Crowbar fixed resistance
Cv	Crowbar variable resistance
cw	Controlled waveform
pr	Polarity reversal
UG	Utility grid (mains)
MG	Motor generator
H.E.	High explosives

Los Alamos: *National High Magnetic Field Laboratory, Los Alamos branch*
 Dr. L.J. Campbell
 National High Magnetic Field Laboratory
 MS-E536, NHMFL-LANL, Los Alamos, NM 87545 (USA)
 Fax: +1-505 6654311
 E-mail: ljc@viking.lanl.gov

At Los Alamos National Laboratory, a huge motor-generator became available from a discontinued fusion experiment. After establishment of the NHMFL as a joint venture of Los Alamos National Laboratory, Florida State University and University of Florida in 1990 (with a static high-field laboratory established in Tallahassee, FL), this generator will be used to power a 60 T magnet with long pulse duration and controllable waveform [34]. While this is under construction, a capacitor bank was built to gain fast access to high fields for experimentation. The first set of 60 T coils for the capacitor installation was designed and made at Leuven. It is proposed to use the generator-driven magnet for providing a 'platform' field for a capacitor-driven insert in order to approach fields of the order 100 T nondestructively.

MIT: *Francis Bitter National Magnet Laboratory at M.I.T.*

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 Massachusetts Institute of Technology NW14-3117
 170 Albany Street, Cambridge, MA 02139-4307 (USA)
 Fax: +1-617 2535405
 E-mail: sfoner@slipknot.mit.edu

This is the oldest of the existing pulsed magnet laboratories, and still going strong. Pioneering work was done with solid helix coils, and the development of the new generation of high performance magnets was inspired by the first coil using a high strength conductor (Cu–Nb microfilaments) that was specifically developed for this purpose [15]. This extended the field range from below 50 T into the 70 T region. The first experiments with pulsed field FIR cyclotron resonance were done at this laboratory, and several other experimental techniques were developed such as the contactless radiofrequency method for measuring the resistance of superconductors.

Merida: *Universidad de Los Andes*
 Prof. Syed Wasim, Centro de Estudios Semiconductores
 Facultad de Ciencias, Universidad de Los Andes
 Merida 5101 (Venezuela)
 Fax: +58-7440 1286

This laboratory has a long duration pulsed magnet similar to Zaragoza and Porto, built at Toulouse.

Moscow: *Kurchatov Institute*
 Dr. A. Lagutin
 Russian Research Center Kurchatov Institute
 Moscow 123182 (Russia)
 Fax: +7-095 1961632
 E-mail: ovi@ozhogin.kiae.su

This is one of the pulsed magnet laboratories with a long tradition, it was established by V. Ozhogin in the early sixties. Pulsed field coils were made with strong Cu–NbTi wire as it is normally used for superconducting magnets. There are now three magnet stations for the measurement of magnetotransport, differential susceptibility and magnetization, and for magnetic resonances in the wavelength range 23–300 GHz [44].

Moscow: *Moscow State University*
 Dr. R.Z. Levitin, Laboratory of Problems for Magnetism
 Faculty of Physics, Moscow State University
 Vorobyevy Gory, Moscow 119899 (Russia)
 Fax: +7-095 9395907
 E-mail: mag@plm.phys.msu.su

This installation was established in 1971, with the purpose of measuring magnetization, Faraday effect, magnetic torque and magnetostriction in the temperature range 4.2–300 K.

Murray Hill: *AT&T Bell Laboratories*
 Dr. G.S. Boebinger, AT&T Bell Laboratories, room 1D-208
 600 Mountain Avenue, Murray Hill, NJ 07974-0636 (USA)
 Fax: +1-908 5823260
 E-mail: bo@physics.att.com

The pulsed field facility at Bell Laboratories was set up a few years ago, and in this short period outstanding results have been achieved [45]. A multisection coil with innovative design features has been developed; peak fields in excess of 72 T have been obtained. The capacitor bank has a peak current of 320 kA under fault condition. The equipment includes a ^3He cryostat. Experiments (mainly magnetoresistance) are on Kondo insulators, 2D electron systems and superconductors.

Osaka: *Research Center for Extreme Materials*
 Prof. K. Kindo, High Magnetic Field Division
 Research Center for Extreme Materials, Osaka University
 Toyonaka, Osaka 560 (Japan)
 Fax: +81-6 8459424

This laboratory was established by M. Date who did pioneering work for the generation of very high pulsed magnetic fields by means of polyhelix coils made from maraging steel [46]. The laboratory has four magnet stations and a complete

set of diagnostic instruments, including equipment for far infrared resonances (developed by M. Motokawa) and optical spectroscopy. Primary research interests are in magnetism, but biological systems have been studied as well. The laboratory has accommodated many visiting scientists. The first symposium on High Field Magnetism was held at Osaka in 1982 [47], resulting in a series of conferences including the present one.

Oxford: *High Magnetic Field Facilities*

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The Clarendon magnet laboratory has a long standing tradition with resistive and hybrid magnets for static fields, and with superconducting magnet design. In recent years, a pulsed field installation was added. The Clarendon group has made substantial contributions to pulsed magnet design by developing a strong conductor with a soft copper core surrounded by a mantle of stainless steel, techniques for vacuum impregnation, and multisection coils. Cooperation between Oxford and Leuven [48] formed the nucleus of EU-ROMAGTECH. In this context, Oxford is developing the concept of the 'platform' field, using a large static field magnet as an outer stage for a pulsed magnet. There is a strong research group for far-infrared spectroscopy and magneto-transport in low dimensional semiconductors and organic conductors, at temperatures into the ^3He range.

Parma: *Parma High Field Laboratory*

Dr. Fulvio Bolzoni, Parma High Field Laboratory
Istituto MASPEC, Consiglio Nazionale delle Ricerche
Via Chiavari 18/A, I-43100 Parma (Italy)
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The 30 kJ pulsed magnet was built in 1974 [49]; in 1990 work on the 1 MJ installation was initiated. This laboratory is specialized in high sensitivity magnetization experiments for the study of magnetic transitions. A 'singular point detection' technique was developed that permits the precise measurement of anisotropy fields in polycrystalline samples.

Porto: *Universidade do Porto*

Prof. J. Bessa Sousa, Centro de Fisica
Universidade do Porto, Praça Gomes Teixeira
P-4000 Porto (Portugal)
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The pulsed magnet installation at this laboratory is similar to those at Zaragoza and Merida; it was built by SOTEREM, Toulouse.

Princeton: *Princeton University*

Prof. P. Chaikin, Department of Physics
Princeton University, Jadwin Hall
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E-mail: chaikin@pupgg.princeton.edu

This facility is now under construction, sponsored by the US National Science Foundation. The energy source is a 200 MW motor-generator from the Princeton Plasma Physics Laboratory. The coil is a hybrid design with a 44 T slow rising background field and an inner 'booster' coil providing 20 T on a shorter time scale, the pulse shape will have a flat top of 100 ms duration. The first pulse is scheduled by the end of 1996.

Sendai: *High Field Laboratory for Superconducting Materials*

Prof. M. Motokawa
High Field Laboratory for Superconducting Materials
Institute for Materials Research, Tohoku University
2-1-1 Katahira, Aoba-ku, Sendai 980 (Japan)
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This laboratory was established in 1981. In addition to the resistive and hybrid static field magnets which are the main purpose of the laboratory, G. Kido built a small pulsed field facility. This is well known for sensitive magnetostriction experiments [50] and magnetization measurements. M. Motokawa will now bring his pulsed magnet from Kobe.

St. Petersburg (Ioffe): *Pulsed Magnetic Field Installation*

Dr. D.V. Mashovets, Pulsed Magnetic Field Installation
A.F. Ioffe Physico-Technical Institute
Russian Academy of Science
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This laboratory was established in 1964. Techniques have been developed for magnetotransport measurements on samples with high resistance, permitting the simultaneous measurement of the zero-field resistance.

St. Petersburg (Polytechnic): *Laboratory of High Voltage Electrophysical Installations*

Prof. G.A. Shneerson
Laboratory of High Voltage Electrophysical Installations

State Technical University
Polytechnical Street h.29, St. Petersburg 195257 (Russia)
Fax: +7-812 5526086
E-mail: shne@phtf.stu.spb.su

This laboratory is well known for extensive research on capacitor-driven single turn coils, both theoretical and experimental, which resulted in the generation of very high fields. More recently, 'bi-conical' coils were developed where only an expendable insert is destroyed in the pulse, as well as pulsed magnets with a very large volume [51].

Sydney: *Australian National Pulsed Magnet Laboratory*
Prof. R.G. Clark, National Pulsed Magnet Laboratory
School of Physics, University of New South Wales
P.O. Box 1, Kensington, Sydney NSW 2033 (Australia)
Fax: +61-2 6633420
E-mail: rgc@newt.phys.unsw.edu.au

The Australian National Pulsed Magnet Laboratory was established in 1991 [52]. The capacitor bank and the 30 T coil were built by Oxford Instruments, and the high field coils were designed and made at Leuven in the context of a cooperative project sponsored by the Australian government. This includes a fibre reinforced coil which was the first to reach 70 T. The laboratory was designed with emphasis on safety and clean data recording, making extensive use of optical fibre transmission. Much attention has been given to all aspects regarding safety; capacitor bank and magnet stations are housed in a blast-proof concrete enclosure. Specialties are optics in the visible and far infrared, ^3He and dilution refrigerators, and apparatus for taking I - V characteristics at peak field. To cover a very large field and temperature range, in addition to the pulsed magnets two superconducting coils have been installed, one for 18 T with a 6 mK dilution refrigerator and one for 16 T with a 20 mK dilution fridge. Dilution fridges can also be combined with the 60 T coil.

Tokyo: *Megagauss Laboratory*
Prof. N. Miura, Megagauss Laboratory
Institute for Solid State Physics, University of Tokyo
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Fax: +81-3 3478 5471
E-mail: miura@issp.u-tokyo.ac.jp

This is the first laboratory specifically built for conducting solid state experiments in megagauss fields; the present installation was built in 1982 [53]. It was realized from the beginning that it is advantageous to have superconducting magnets and nondestructive pulsed magnets under the same

roof, sharing the instrumentation for covering the entire range of magnetic fields. There are three capacitor banks for generating nondestructive pulsed fields, using mostly coils impregnated with ice. The 110 kJ bank is configured as a transmission line to obtain a flat top waveform. The instrumentation is advanced and complete, including an optical multichannel analyzer, far infrared optics and instrumentation for magnetotransport (also contactless) and magnetization experiments, at temperatures into the ^3He range.

Toulouse: *Service National des Champs Magnétiques Pulsés*
Prof. S. Askenazy
Service National des Champs Magnétiques Pulsés
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This laboratory has a long tradition in innovation and outstanding research and it is now the largest pulsed field laboratory in Europe [54]. There is instrumentation for magnetotransport and magnetization measurements with extreme sensitivity, and for far infrared resonances. The cryogenic equipment includes two dilution refrigerators, and high pressure apparatus for use in pulsed fields has been developed. A special feature of this laboratory is the operation of coils at 63 K by pumping on the nitrogen. Releasing the pressure just before the field pulse results in low noise due to the absence of bubbles in the nitrogen bath.

The laboratory is presently moved into a new building where a modular 12 MJ capacitor bank with 10 measuring stations is under construction; this will become operational by the end of 1995. The new laboratory includes generous facilities for sample preparation and for the fabrication of strong conductors.

Tsukuba: *Tsukuba Magnet Laboratories*
Dr. G. Kido, Tsukuba Magnet Laboratories
National Research Institute for Metals
Sengen 1-2-1, Tsukuba-shi, Ibaraki-305 (Japan)
Fax: +81-298 531199
E-mail: kido@nrim.go.jp

The construction of this new laboratory started in 1988, it will be officially opened in 1995. Tsukuba has been well known for the development of high performance superconducting wires; it was a natural outgrowth of this work to develop high strength microfilamentary materials. The Cu-Nb material developed at Tsukuba is the best material presently available for making pulsed magnets; coils made with this wire in cooperation with Leuven are now holding the world record for nondestructive pulsed magnetic fields [55].

Vienna: *Technische Universität Wien*

Prof. R. Grössinger, Institut für Experimentalphysik
 Technische Universität Wien
 Wiedner Hauptstrasse 8-10, A-1040 Vienna (Austria)
 Fax: +43-1 5863191
 E-mail: rgroess@evax.tuwien.ac.at

This laboratory was established in 1975, it houses a number of special measuring systems for measuring magnetization and magnetostriction in the temperature range between 4 K and 1000 K. Measurements are mainly on magnetic materials, among others the anisotropy field by the singular point detection method. A controlled waveform 40 T magnet is under construction, using 10 MW (1000 V, 10 kA) from the mains.

Worcester: *Clark University*

Prof. C. Agosta, Physics Department
 Clark University
 950 Main street, Worcester, MA 01610 (USA)
 Fax: +1-508 7938861
 E-mail: cagosta@clarku.edu

This laboratory was set up for the study of organic conductors, a research area that holds great promise due to the large variety of effects that occur in these materials at high fields and low temperatures. Emphasis is placed on the development of cryogenic equipment adapted to pulsed field experiments, e.g. ^3He cryostats made entirely of plastic, a design which is characterized by particular elegance and simplicity.

Wroclaw: *International Laboratory of High Magnetic Fields and Low Temperatures*

Dr. T. Palewski, International Laboratory
 Gajowicka 95, Wroclaw 53-529 (Poland)
 Fax: +48-71 612721
 E-mail: mlspmint@pwr.wroc.pl

This laboratory was launched in 1968 as a cooperative venture of the Academies of Science of the USSR, DDR, Bulgaria and Poland. The political changes in these countries have resulted in financial difficulties but the work is continued in cooperation with different countries and with a grant from, among others, the European Union. One of the new projects is the construction of a 60 T magnet with 0.1 s pulse duration. A specialty of the laboratory is research under high pressure.

Zaragoza: *Universidad de Zaragoza*

Dr. P.A. Algarabel or Prof. A. del Moral
 Laboratorio del Magnetismo
 Departamento Fisica de Materia Condensata

Universidad de Zaragoza, E-50009 Zaragoza (Spain)
 Fax: +34-76 553773

The facility was built by SOTEREM (Toulouse) on the basis of technology developed at the Toulouse pulsed magnet laboratory; it became operational in June 1994. Measuring equipment is for magnetization and magnetostriction in a He continuous flow cryostat (1.5–325 K).

4. Destructive pulsed magnets

Above the megagauss limit which corresponds to a pressure of 4 GPa, coils are destroyed during the pulse by the combined action of Maxwell stress and Joule heating. The dominant factor is the mechanical force; coils are actually held together by localized inertia. Due to the compressibility and the related finite speed of sound, inertial confinement is affected only by a relatively thin layer of the conductor at the interface with the magnetic field. From this layer, a shock wave propagates into the material; at the outer surface, this is reflected as a rarefaction wave. The finite wall thickness of the coil comes into play only after the rarefaction wave arrives back at the inner surface. Megagauss generators are optimized by using just enough material to avoid this condition before peak field is reached (until this moment the interface behaves as if the coil were infinitely thick), typically this happens in a time interval of the order of a microsecond. Since this is a fundamental limitation of the time scale, all one can do is to devise experiments that can be carried out in the short time available. Apart from obtaining still higher fields, this is the real challenge for the coming years.

Arzamas: *Scientific Research Institute of Experimental Physics*

Dr. M.I. Dolotenko, VNIIEF
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 E-mail: otd4@expd.rfnc.nnov.su

This is one of the few laboratories where megagauss research originated more than 30 years ago. This outstanding research was originally inspired by the late academician A.D. Sakharov, and subsequently the research was directed by the late academician A.I. Pavlovskii [56]. Absolute record fields were obtained in this laboratory by means of explosive-driven flux compression, using the ingenious method of 'cascades', and an explosive-driven megajoule generator (MC-2) for the initial field. Devices are so reliable and reproducible that they are well suited for experimental applications. Some experiments are now conducted in collaboration with the Los Alamos megagauss laboratory.

Table 5

Magnet laboratories generating megagauss fields destructively

Laboratory	W [MJ]	U [kV]	I [MA]	H.E. [kg]	B [T]	i.d. [mm]	t_r [μs]	dB/dt [T/μs]	t_p [μs]	Method
Arzamas	1	25	2.5–7	16	900–1300	9–5	17	400	<0.5	Implosion
	100	200	100	180	1700	5	16	1500	<0.2	MC2 + implosion
Berlin	0.2	60	7.5		150–300	10–5	2	120	1	RG single turn
Los Alamos	0.7	20	2	3	100	19	14	10	4	B I
	2.4	20	4	8	230	11	14	30	4	
St. Petersburg TU	0.8	50	13		70	35	7	15		SG single turn
	0.035	50	2.3		360	2	1	5600		SG single turn
Tokyo	5	40	6		550	10	4	150	0.3	Em-implosion (SG)
	1.5	10	0.5		3.2	200	10 ⁴		4000	'Seed field'
	0.1	40	2.5		150–280	10–3	2.5	95	1	Single turn

Berlin: *Humboldt Universität*

Prof. M. von Ortenberg, Lehrstuhl Magnetotransport

Fachbereich Physik, Humboldt Universität

Invalidenstrasse 110, D-10115 Berlin (Germany)

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E-mail: orten@physik.hu-berlin.de

This is the first laboratory in Europe where megagauss fields will be generated by means of the single turn coil technique. The facility is now under construction and will become operational before the end of 1994. It features a new capacitor bank design with a low inductance strip-line, with control and data acquisition via optical fibres, at temperatures down to 2 K [57]. The facility includes optics in the infrared and far infrared, nondestructive pulsed magnets (see Table 3) and three superconducting magnets for fields up to 15 T.

Los Alamos: *National High Magnetic Field Laboratory, Los Alamos branch*

Dr. L.J. Campbell

National High Magnetic Field Laboratory

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C.M. Fowler who is still active at this laboratory was the first to publish results from explosive-driven flux compression in the open literature [58]. The development included flux compression by cylindrical implosion and by explosive-driven generators in helical and plane geometry; the latter are now mostly used for experimentation (see Table 5) at cryogenic temperatures. In cooperation with Florida State University and University of Florida, a successful bid was made to the NSF for setting up the new National High Magnetic Field Laboratory. This makes explosively generated

megagauss fields available for the first time to a broad user community [34].

Novosibirsk: *Lavrentyev Institute for Hydrodynamics*

Dr. G.A. Shvetsov, Lavrentyev Institute for Hydrodynamics

Siberian Division of the Russian Academy of Science

Novosibirsk 630090 (Russia)

At Novosibirsk, large containment chambers have been set up that permit indoors experimentation with high explosives. The development is focused on explosive-driven generators that can generate huge bursts of electromagnetic energy [59]. These are used to power railguns for obtaining extremely high speeds; among others these high speed macroparticles can be used to study the equation of state of solids.

Tokyo: *Megagauss Laboratory*

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The megagauss laboratory at ISSP is the largest facility for indoors experiments with megagauss fields. It was established around 1970 by the initiative of professor S. Chikazumi and developed by N. Miura and coworkers [53]. In order to obtain the highest fields, electromagnetically driven flux compression was chosen as the primary method. After a series of exploratory experiments, a very large capacitor bank was built (by the Nichicon company) with the aim of obtaining fields up to 1000 T. This was an expansion of scale by an order of magnitude, and many problems had to be solved for obtaining the highest fields reliably; optimization of the implosion devices is still in progress. Electromagnetic implosion involves a delicate balance

between many interdependent parameters; therefore the device development is supported by sophisticated numerical calculations. At present, fields in excess of 500 T have been achieved and can be used for infrared resonances at cryogenic temperatures [60].

At a later stage, an enlarged single turn coil generator as originally developed at Chicago [61] was added [62]. This turned out to be a practical instrument and an excellent workhorse for daily use, with a turnaround time of less than one hour between experiments. A big advantage of the single turn coil technique is the fact that the cryostat and the sample are not destroyed although the coil explosion is quite violent. Experiments are mainly infrared resonances at temperatures from above room temperature into the liquid helium range (gas flow cryostat). Surprisingly, it was possible to perform successful measurements of magnetization and magnetoresistance in this difficult experimental environment.

5. Outlook to the future

As compared to previous reviews, there has been a substantial increase in the number of magnet laboratory facilities, as well as in the performance of the magnets and the research. There are now three major laboratories that meet the requirements of the new generation of static field magnets, with power supplies in the 20 MW range. The laboratory in Grenoble, France, underwent a major upgrading in 1991, and two very large magnet laboratories have just been established at Tallahassee/Los Alamos in the USA and at Tsukuba in Japan, both featuring large hybrid magnets as well as pulsed magnet development. We will certainly see a rapid increase in maximum field strength of static field magnets in the coming years and a significant advance in technology.

The drive towards higher fields has resulted in an upsurge of research in pulsed magnetic fields and in the establishment of new facilities of all sizes. Experimentation with pulsed magnets has been greatly enhanced by the development of new techniques for digital data recording and miniaturization. For solid state research, pulsed magnets have been combined with dilution refrigerators and high pressure equipment. This appears to be just a beginning, the new techniques have not yet been fully exploited and much further development is anticipated for the coming years.

For magnet design, there are two challenges in sight: a 50 T hybrid magnet and a 100 T magnet with long pulse duration. In Europe, several magnet laboratories are trying to set up a consortium to meet the challenge of developing 100 T nondestructive magnets. There is much optimism that these developments will bear fruit around the turn of the century.

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