STATUS AND DEVELOPMENTS AT THE HIGH FIELD MAGNET LABORATORY OF THE UNIVERSITY OF NIJMEGEN

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A hybrid magnet system generating a maximum field strength of 30.4 T has been succesfully tested and been put into operation at the Nijmegen High Field Magnet Laboratory. A short overview is given of the present installations and the operating characteristics of the new hybrid magnet, Nijmegen II, and its peripheral facilities are discussed.

Introduction

The University of Nijmegen has been operating a facility to generate high static magnetic fields since 1976. The facility is configured around a 6 MW electric power supply and the associated water cooling system; the specifications are given in Table 1. The Nijmegen High Field Magnet Laboratory (NHFML) is housed on two floors of the physics wing in the Faculty of Science at the University of Nijmegen.

Electrical Power and Cooling

The dc current to energize the magnets is provided by two 3 MW power supplies (300 V×10 kA), one of which is schematically shown in Fig. 1. They are usually operated in parallel. Each unit consists of a transformer, diode rectifiers, a passive and an active filter.

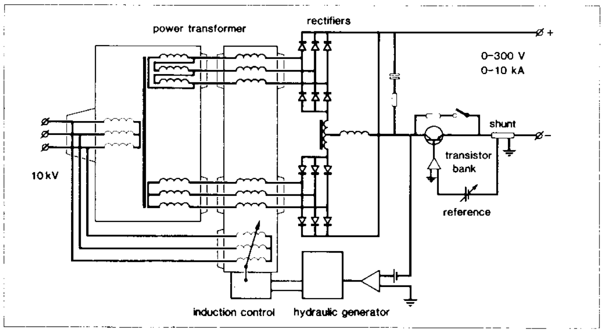

Figure 1. Schematic of a 3 MW power supply unit.

The transformer has two sections, one of which has rotating primary coils (induction control), each with two secondary windings. The secondary windings of the two sections are connected in series, and by adjustment of the induction control the secondary phase voltage may be set between 5 V and 165 V, which is then passed on to a three-phase rectifier bridge and a passive LC-filter. As the two secondary phase voltages are phase-shifted over 30° with respect to each other, the basic ripple on the magnetic field will be at 600 Hz.

Table 1. Specifications of cooling and electrical power supplies.

Water cooling	
Cold buffer	maximum 150 tons of ice in a 400 m^3 basin (18 MWh), compressor driven refrigerator cooled with ground water
primary circuit	maximum flow 260 m^3/h, 5°C to heat exchanger
secondary circuit	deionized water (< 0.5 μmho/cm), nominal temperature 18°C
high pressure pumps	400 m^3/h at up to 23 bar
3 MW Power supply (2 units)	
Primary voltage	10 kV_{ac}
Secondary voltage	0 - 300 V_{dc}
Secondary current	0 - 10 kA_{dc}
Overload capability	100% for 1 min, once every 15 min
Current stability	short term (1 h): 0.01% of setting at ±5% line voltage variation or at ±30% load variation long term (10 h): 0.1% of setting at ±20°C ambient temperature variation
Ripple (at full power)	15 mV_{pp} (600Hz)
Current setting	better than 0.1 A
Speed of control	30 V/s over the entire range 1000 V/s over ±6 V around setting
Tracking error	< 0.1% for sweeps < 110 A/s
Modulation	14 V_{pp}, 20 - 100 Hz

0018-9464/88/0300-1397$01.00

Further regulation is provided by a transistor bank of 2000 germanium transistors in parallel. The maximum voltage across this transistor bank is 18.5 V, the nominal voltage will be about 10 V where coarse control is realized via an hydraulic system that will set the induction control. The voltage across the transistor bank may be varied rapidly between +3 V and +17 V for the purpose of accurately regulated magnetic-field sweeps, or of magnetic-field modulation. The reference for the power supplies is set by means of a remote panel controlled by the experimenter and may represent any time-profile of the magnetic field within certain limits.

The power units have a short-term overload capability of 12 MW, but present contracts with the Utility Company limit the available electric power to 8 MW. A nominal power of 6.3 MW is available on workdays from 23:00 h to 8:00 h, and at weekends around the clock. Daytime operation is possible, but with certain restrictions, starting after 13:00 h, except during four weeks in December. On a typical day two shifts of nominally four hours will be scheduled, although occasionally very long sessions lasting until the early morning will take place. Over a one year period about 1500 user-hours are available (after allowance for maintenance and testing). In each of the last five years the installation has been used during an average of almost 700 user-hours, with an average energy consumption of 0.77 MWh per user-hour. Running of the extremely high field hybrid-magnet systems is very labour-intensive and is offered only to a limited extent.

The cooling of the resistive magnets and of the electrical power supplies is achieved with a closed-cycle water cooling circuit. As the cooling water is in direct contact with the current carrying plates, the water in this circuit is deionized. Fig. 2 gives a concise overview of the cooling installation. For environmental reasons and because there is no river nearby, it was decided to use ground water for the ultimate cooling. In this way the rate of heat transfer is only small, therefore cold is buffered in a stock of frozen water.

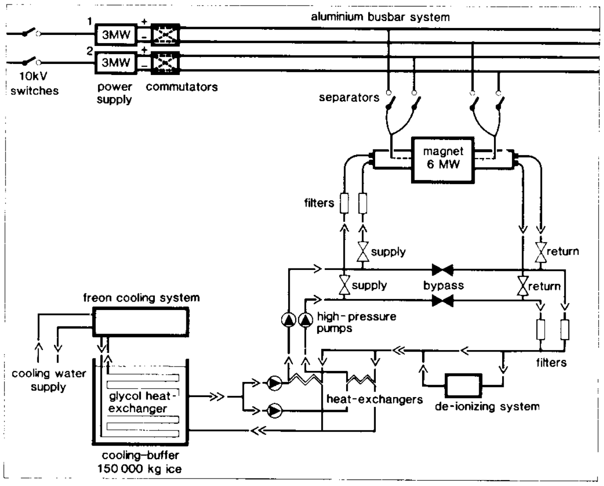

Figure 2. Schematic layout of the installation of the NHFML, indicating a magnet station, the power supplies, and the cooling system.

The High Field Magnets

The NHFML has five magnet stations operational, the present configuration is listed in Table 2 together with some specifications of the magnets. The magnets are being run and maintained by the laboratory staff. There is no program in Nijmegen to develop and construct magnets however. The hybrid magnet Nijmegen I has been in operation since 1978 and has been built under a collaborative contract at M.I.T.; a second, more advanced hybrid magnet system has been in operation since early summer 1987.

Table 2. Experimental stations at the NHFML.

Magnet System	Maximum field (T)	Bore (mm)	Power (MW)	Homogeneity in 1 cm DSV
1. Hybrid Magnet N I	25.4	32	5.70	3×10^{-3}
2. Bitter Coil	15.2	60	5.85	2×10^{-4}
3. Bitter Coil	14.8	53	5.85	1×10^{-5}
4. Duplex Bitter Coil	20.0	32	5.80	1×10^{-3}
5. Hybrid Magnet N II	30.4	32	5.50	3×10^{-3}

Nijmegen II: This latest expansion of the NHFML, the 30 T hybrid magnet which we call Nijmegen II (See Fig. 3), has also been designed and built at the M.I.T. Francis Bitter National Magnet Laboratory in cooperation with the University of Nijmegen. The design of the magnet, the features of the subcooled superfluid helium cryostat and the first testing at M.I.T. have been reported earlier [1,2,3]. The superconductive coil has been designed for operation at 4.2 K and at 1.8 K, and it will then generate 8.3 T at 1500 A or 11 T at 2000 A respectively. The insert consists of two concentric radially-cooled Bitter coils which for their compression rely mainly on a set of iron armatures at either end of the stacks. The iron armatures also contribute to the total magnetic field. The system has now been installed in Nijmegen and has been tested to full power.

In the NHFML the cooling of the radiation shield and the precooling of the superconductive coil down to about 15 K is accomplished by a Philips Cryogenerator in a similar way as with the 25 T hybrid magnet, Nijmegen I [4]. Cooldown from room temperature to 15 K takes about 200 hours. After cooling down and before transfer of liquid helium into the cryostat the 20 K cooling system is shut off, and the 20 K cooling panel, which surrounds the coil vessel, is evacuated to minimize heat input into the coil space. The cryogenerator is kept running to provide cooling for the 80 K radiation shield. It takes about 90 minutes to fill the coil space and the reservoir with liquid helium. Another 75 minutes are required for cooling the coil space from 4.2 K to 1.8 K, using the cooling power of two 1250 m^3/h vacuum pumps. The total amount of liquid helium required for filling and cooldown, inclusive of transfer losses and boil-off, is about 550 liters.

Performance tests: System testing in Nijmegen was performed in three phases: a) insert coils only, b) combined systems, insert coils and superconductive magnet, at 4.2 K, and c) combined systems at 1.8 K. The two concentric radially water-cooled coils are energized in series with a maximum current of 20 kA, the voltage drop across the outer coil is then 151.5 V and across the inner coil 121.0 V. The maximum field of 19.6 T in the 32 mm dia. bore is obtained at a power of only 5.5 MW. The efficiency figure $B(d/W)^{1/2}$ (where B is the magnetic field strength in T, d the room temperature bore in cm, and W the electrical power in MW) is therefore 14.9 [5]. The maximum magnetic field strengths obtained in these tests are listed in Table 3. With Nijmegen II operating at 1.8 K and a power consumption of 5.5 MW we have reached a field of 30.4 T in a 32 mm bore.

Table 3. Maximum field strength for the hybrid magnet Nijmegen II.

	$I_{w/c}$ (kA)	$I_{s/c}$ (A)	$B_{w/c}$ (T)	$B_{s/c}$ (T)	B_{tot} (T)
a.	20	0	19.6	0	19.6
b.	20	1500	19.6	8.3	27.9
c.	20	1950	19.6	10.8	30.4

Cryogenics: The standing loss with coil space and reservoir filled at 4.2 K is equivalent to a heat input of about 6 W. With liquid in the coil space only, boiling off through the reservoir, this is reduced to 4.5 W. The normal operating practice for hybrid magnet systems is to run the superconductive coil to its full current and sweep or set the field of the insert coils as required by the experiment. Under these conditions the heat input, and hence the helium consumption, is considerably higher: the heat loads on the reservoir and the 1.8 K coil vessel amount to 40 W and to about 20 to 25 W respectively. The reservoir losses mainly come from two sources: a) The ohmic losses of the two MULTILAM contacts, between the

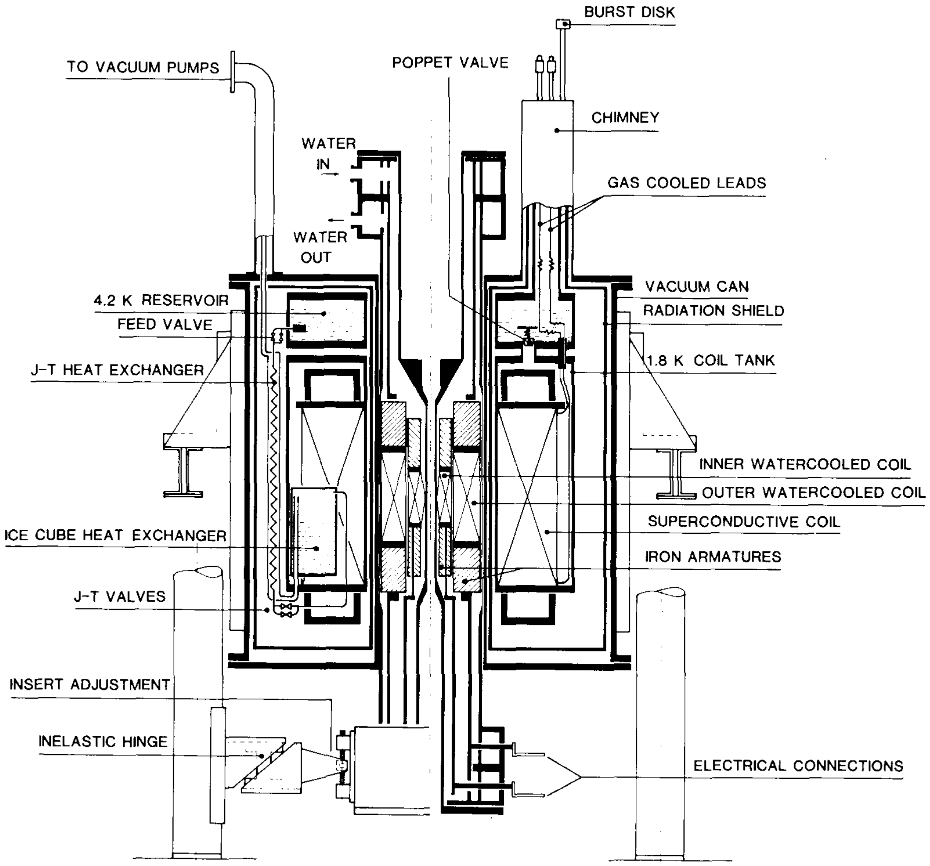

Figure 3. Cross section of the hybrid magnet system, Nijmegen II.

gas-cooled leads and the superconductive busbars in the reservoir, are as much as 27 W (and seem to increase with every operation). Since the contacts are immersed in liquid this figure translates for the full amount into boil-off. b) The system design, with a reservoir containing about 70 liters, is based on the assumption of continuous transfer during operation. With the present transfer technique however we introduce a loss of about 10 W (13 l/h). Modifications are planned to essentially eliminate these two sources.

From the data we have collected so far it is not possible to get a clear picture of where the heat load on the 1.8 K vessel originates. Coil losses cannot be ruled out at this point but we have seen evidence for thermal leaks: interaction forces between the superconductive coil and the insert plus its iron armatures cause the superconductive coil to readjust its position when it is being energized.

Peripherals: The decision to apply a cryogenerator with this magnet was based on the excellent experience with our first hybrid magnet system, Nijmegen I. A cryogenerator (which requires a significantly smaller investment than a liquefier) is a very convenient device for cooling down such a big coil, especially if (like in our case) the magnet is not to be kept cold permanently. The cooldown process needs very little attention and no liquid nitrogen is needed.

The 2000 A power supply for the superconductive coil has been built by Holec in Hengelo. It has SCR rectifier bridges. The firing angle of the SCR's can be controlled between -180° and +180° thus enabling the supply to deliver as well as to absorb power at up to 20 V. The shunt is a dc current transformer, yielding a stability of 10^{-4}.

The dump resistor is made of iron strips (4×30 mm^2 cross section) and has sufficient thermal mass to absorb the superconductive coil's magnetic energy of 11 MJ at a moderate temperature rise of about 150°C. The discharge time constant is 22 seconds. The dump resistor is connected parallel to the superconductive coil rather than parallel to the dump switch. The advantage of far better control characteristics of this set-up more than outweighs the inconvenience of having a small discrepancy between shunt voltage and actual coil current during sweeps. Besides, this discrepancy can easily be compensated.

A quench detector was developed based on the detect/dump protection scheme described by Iwasa and Sinclair [6], and by Ishigohka and Iwasa [7]. The 24 pancake voltages are fed into as many operational amplifiers and added, with equal weights and with the right sign. Instead of isolation amplifiers we used ordinary operational amplifiers (308) with a voltage divider (1:10) at the input. All inputs are clamped to ±10 V for protection during a dump. With the detection level and circuit bandwidth presently used, the highest temperature in the normal zone during a quench/dump sequence is estimated to remain below 150 K.

Conclusion

With the acquisition of its new 30 tesla hybrid magnet system, the NHFML can offer the highest available static magnetic fields. It also puts at the disposal of its users a wide selection of cryogenic equipment, ranging from a top-loading dilution refrigerator to helium-flow cryostats and ready-to-use inserts. Users can also draw on a large pool of electronic and spectroscopic instruments.

The NHFML is presently encouraging a more intensive use of its facilities by visiting scientists.

Acknowledgements

The authors are indebted to J. van Huet for designing the control unit for the 2000 A power supply, as well as the quench detector; to H. Van Luong for making the quench detector really work, for all the other electric and electronic hardware and, last but not least, for developing the software which enables us to keep a close eye on the system from a comfortable distance. We thank J. Rook for all the vacuum work, the gas handling system, all the mechanical odds and ends that came along and especially for designing and building a perfect, adjustable support for experimental cryostats, within the limits set by all the other hardware.

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