# High Field Magnet Laboratory at Nijmegen

## Facilities and Experiments

### H.W. Myron, Nijmegen

Magnet laboratories fall into a size category all to themselves: not large for example on the scale of CERN or ILL, but substantial enough to encourage multi-laboratory and international cooperation. Here, I should like to encourage this by describing the various magnets and facilities available at the "Laboratorium voor Hoge Magneetvelden" at the *University of Nijmegen* in The Netherlands, as well as some of the research programmes planned or underway.

At present, the Nijmegen facility has five magnet stations: a 25.4 T hybrid magnet, a 20 T Bitter magnet and three 15 T Bitter magnets of various characteristics (see Table 1).

A hybrid magnet is a superconducting solenoidal magnet concentrically surrounding a water-cooled resistive magnet. Nijmegen I, our first hybrid, has a "super" field of 8.4 T in a room temperature bore of 40 cm. The superconducting material is Nb-Ti operating at 4.2 K. The twenty-one individually wound superconducting coils sit in a cryostat which can accommodate 320 l of liquid helium. The cryostat is precooled by a two stage (80 and 20 K) cryogenic pump, the cool-down from room temperature taking approximately seven days.

In the warm bore of the superconductor, two Bitter magnets are concentrically placed; the working radial diameter of the "big" field from the superposition of the superconductor and Bitter fields is 32 mm, in which we generate a field of 25.4 T. The "1 ¼" in bore is a standard size in Nijmegen and at the Francis Bitter National Magnet Laboratory of the Massachussetts Institute of Technology in Cambridge. The hybrid design is preferred for the the highest field operations simply because of restrictions on the size of the power supply available for the resistive (Bitter) magnets. For example, to generate a 25 T field by resistive means only, requires a power supply of some 10 MW, whereas with an 8 T boost field from the superconductor of a hybrid, one can generate the same field with 5.4 MW — a difference of 4.6 MW. For a 50 T magnet, the difference in power requirements for a hybrid magnet with a 10 T superconducting background compared to a purely resistive magnet is 29 MW!

The generation of a magnetic field in the so-called resistive magnets is conceptually straightforward. One needs a current loop (in our case of 20000 A) and the loop is created by a series of stacked Bitter coils, in which at a given azimuth a wedge is cut from the insulation layer whereupon the current jumps to the next copper coil and so forth. The stacking of the copper coils varies according to field requirements, but the simplest version is shown in Fig. 1. The bore of the magnet is of course the centre, the small holes are for cooling water and an outer annulus is used to bolt the stack in place.

The cooling for the resistive magnets is provided by a demineralized water installation with a flow of $3 \times 10^5$ l/h. The entry temperature is about 10° C and the water is warmed by 20 deg when the magnet is operating at full power. The primary cooling is provided by an ice bunker of 150 ton, which has a capacity of 18 MWh. The ice is generated by two compressors which in practice ensures continuous operation. AC power is provided by the local electric company which we transform and rectify. Weekdays, we begin operations at 13:00 and in principle may continue until 08:00 in the morning. During the weekend, we can have electricity on a 24 hour basis. Even though we have on occasion worked around the clock and started shifts at 3 in the morning (de hond shift) we try to schedule at more convenient hours, depending on the demand.

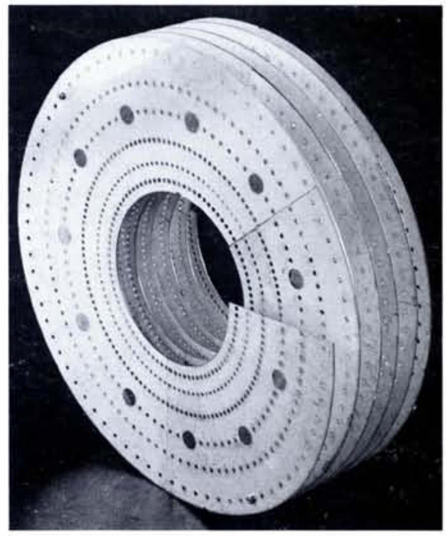

*Fig. 1 — The conductor of a Bitter solenoid pulled open; small holes are for the passage of cooling water and larger holes are to clamp the coil in place.*

The Bitter design, however, is by no means unique in creating fields in water cooled resistive magnets. Recently a team at the Grenoble magnet laboratory, Service National des Champs Intenses and Max-Planck-Institut, have generated continuous fields of 25 T using a polyhelix design. A polyhelix as the name implies is made up of concentric cylinders which are water cooled in the region between the copper helices. The polyhelix magnet will form the resistive part of their forthcoming hybrid magnet.

The Nijmegen hybrid magnet reflected in Fig. 2 is still the world record holder for continuous DC fields at 30.06 T. Since the mid 1970's, we have cooperated with the National Magnet Laboratory to make the highest fields available to scientists at our respective laboratories. By pooling our financial resources we were able to accomplish our mutual goals which independently would most probably not have been feasible or difficult at best. This was undoubtedly also one of the motivations for cooperation between France and the Federal Republic of Germany.

Soon we expect another hybrid magnet, Nijmegen II, which all being well, will at the time of reading, achieve a continuous field of between 32 and 33 T at MIT. It will have a "super" field of 11 T using Nb-Ti operating at 1.8 K and the resistive part will achieve 22 T, once again with the standard bore size.

**Table 1 — Characteristics of magnets at the Nijmegen High Field Magnet Laboratory**

| Magnet | Maximum Field (T) | Homogeneity (in 1 cm diameter of spherical volume) | Room Temperature Bore (cm) |
|---|---|---|---|
| Hybrid Magnet 1 | 25.4 | $3 \times 10^{-3}$ | 3.2 |
| Hybrid Magnet 2* | 30.0 | $3 \times 10^{-3}$ | 3.2 |
| Bitter 2 | 14.5 | $5 \times 10^{-5}$ | 5.3 |
| Bitter 1/3 | 15.0 | $1 \times 10^{-4}$ | 6.0 |
| Bitter 4 | 20.0 | $1 \times 10^{-3}$ | 3.2 |

* planned for early in the New Year.

Having operated at MIT, the 33 T hybrid will be shipped to Nijmegen where we expect to attain DC fields of up to 30 T. The difference in peak fields available at Nijmegen and MIT is reflected by the maximum power available (6 and 10 MW respectively). MIT will construct a second version of Nijmegen II which will remain in Cambridge.

The Japanese at Tohoku University in Sendai have also made a serious effort in achieving high DC magnetic fields through the construction of hybrid magnets. Soon, it is expected that they will also have a > 30 T hybrid system. The editors of the Guiness Book of Records will undoubtedly be very busy with magnets in this Olympic year.

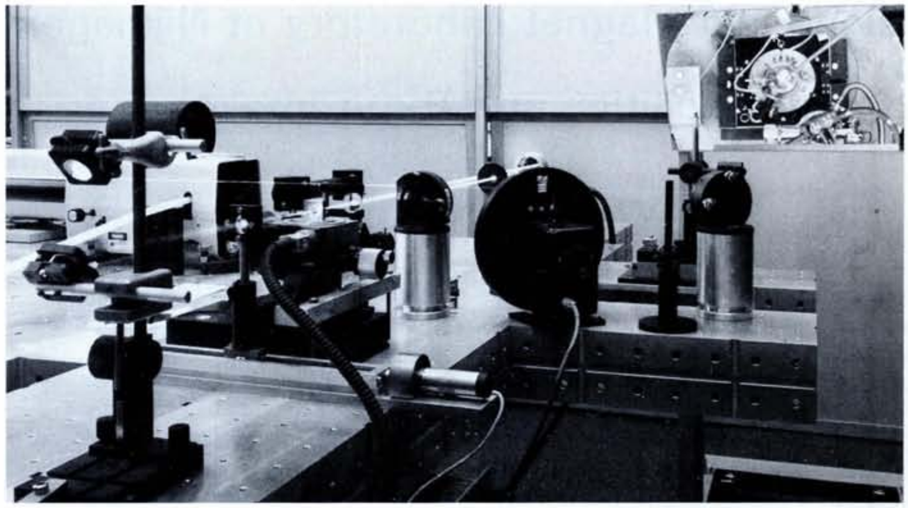

*Fig. 2 — Picosecond light pulses from a CW dye laser which is synchronously pumped by a mode locked Kr-ion laser is used to study electron-hole recombination in quantum wells in high magnetic fields. The hybrid magnet is seen through the mirror on the upper right hand side of the photograph.*

**User Interest**

The scientific facilities available to users of the laboratory include a variety of cryostats with a temperature range from milliKelvin to room temperature. The dilution refrigerator in a 15 T magnet is shown in Fig. 3. Far infrared and picosecond laser systems are also available as well as a wide variety of electronics. Now, I should like to go into some detail regarding the collaborations on a multi-laboratory and/or international scale.

A very intriguing problem in solid state physics using high magnetic fields is the Quantum Hall Effect (QHE) and the fractional QHE discovered respectively by von Klitzing, Dorda and Pepper (1980) and Tsui, Gossard and Störmer (1982): for a given value of magnetic field the Hall resistivity of a two-dimensional electron gas become an integer (or fraction) of $h/ke^2$ where $h$ is Planck's constant, $e$ is the electron charge and $k$ is the integer or fraction. The discovery of the integer effect was so significant that

*Fig. 3 — The dilution refrigerator in a Bitter magnet. The magnet is enclosed in a wooden box for safety reasons.*

von Klitzing won the Hewlett-Packard Prize of the European Physical Society in 1982 while Tsui, Gossard and Störmer (Bell Labs) won the Buckley Prize of the American Physical Society this year for their discovery of the fractional effect.

The integer effect was first seen in a Si-MOSFET where the two-dimensional electron gas (2DEG) is confined between Si and $SiO_2$. At sufficiently high magnetic field the localized and extended electron states, respectively the tail and centre of the Landau level, are separated and the Hall resistance reaches its integer quantized value. For highly disordered samples of low mobility, the half-widths of the Landau are wide and one does not see the effect. Si MOSFETS have an "intermediate" mobility of $\sim 10^4$ cm$^2$/V s where a sufficient number of localized states are present; hence the observation of the integer plateaus. Using DC techniques, fractions are not observable for such low mobility samples. The 2DEG formed by a heterojunction of GaAs and AlGaAs can have considerably higher mobilities ($> 10^6$ cm$^2$/V s), hence the number of localized states decreases and the influence of the electron-electron interaction is enhanced. This enhanced interaction opens up gaps in the Landau level leading to a new ground state and the fractional QHE.

Recently, we in cooperation with Mike Pepper, Adrian Long and others at the Cavendish Laboratory, Cambridge, England have pooled our resources in order to study the problem of the 2DEG in a high magnetic field. We thought that one of the most promising types of experiment was to study the behaviour of the integer levels at very high frequency (45 MHz $> f >$ 0.5 MHz). (Both the integer and fractional QHE were discovered using DC techniques.) The reasoning behind a high frequency experiment was that the states in the tails of the Landau levels are effectively delocalized at high frequencies. This is very similar to relative widths of the QHE plateaus observed in low and high mobility GaAs-AlGaAs heterostructures. There, once again, the low mobility samples show wide integer plateaus (no fractions) while the high mobility samples show narrow integer plateaus with fractions. In our experiments, we should be able to control directly the degree of localisation by varying the frequency.

We observed, in a Si-MOSFET, a decrease in the integer plateau width which is clear evidence that frequency is removing localisation, so narrowing and finally eliminating the plateau of quantised resistance. Correspondingly, we observed structure related to a 4/3 and 5/3 fill factor whose features moved with magnetic field in the same way as that corresponding to the integer QHE! This is shown in Fig. 4. Future work on the frequency effect is in progress.

Other projects related to localization and/or the QHE which find a place at the laboratory are for example, with Philips Research Laboratory, Technische Hogeschool Delft, Catholic University of Louvain, Max-Planck Institute — Stuttgart, Laboratoire Electronique Physique — Paris and Forschungsinstitut der Bundespost. These researchers come or send their specimens since we have some unique spectroscopic facilities incorporated with the magnetic fields.

Another project within the laboratory which is also unique as well as physically appealing is the "Phase Diagram of a Ferroelectric Chiral Smectic Liquid Crys-

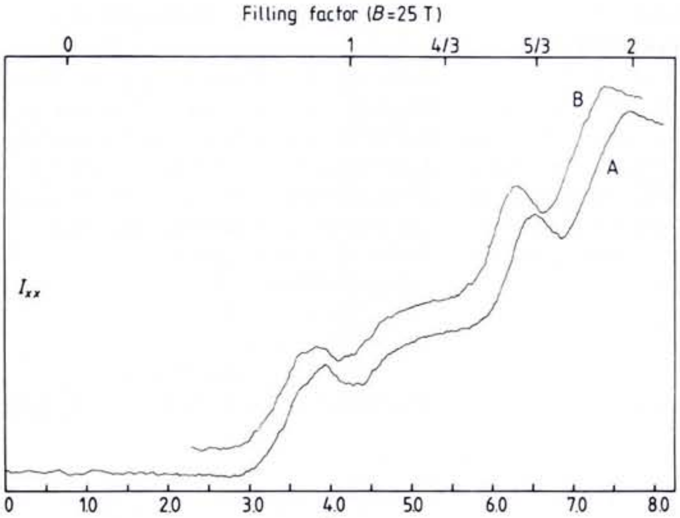


*Fig. 4 — Fractional Quantum Hall Effect in a Si-MOSFET showing characteristic structures of Landau level filling factors at 1, 4/3, 5/3 and 2. The measurements were performed at a frequency of 45 MHz, curve A is at 25 T and curve B at 24 T.*

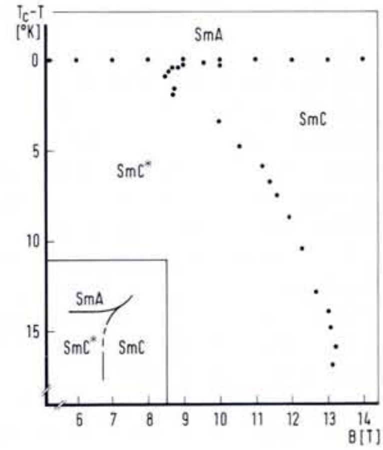


*Fig. 5 — Phase diagram of a chiral smectic liquid crystal. The insert shows the predicted phase boundaries from Michelson.*

tal near the Lifshitz Point". This collaborative effort with the research groups of R. Blinc of the J. Stefan Institute in Lujbljana Yugoslavia and P. Wyder of our laboratory has led to some definitive conclusions regarding the nature of the phase transition near the $\lambda$ point.

The Lifshitz point first introduced by Hornreich, Luban and Shtrikman (1975) is a special case of a triple point between the disordered, uniformly ordered and modulated order phases. Not too long after the introduction of the Lifshitz point (LP), Michelson (1977) proposed theoretically a concrete realization of the LP on the H-T diagram of a chiral smectic liquid crystal if the magnetic field is applied parallel to the smectic layers. More than five years after its prediction the first observation of the phase diagram of the chiral ferroelectric smectic liquid crystal p-decyloxybenzilidene-p'-amino-2-methylbutylcinnamate (DOBAMBC) in an external magnetic field suggested that a LP exists between the disordered smectic-A, the helicoidally ordered-C* and the homogeneously ordered smectic-C-phases. This collaborative work of Igor Musevic et al. (1982) measured the $T_c$-$H$ phase diagram in a magnetic field up to 14.5 T. This is shown in Fig. 5 along with the predicted phase diagram shown in the inset.

The data of Fig. 5 also suggests a reentrant C* phase above 8.5 T which cannot be quantitatively described by the model of Michelson or de Gennes (1968). Further studies by Igor Musevic *et al.*, which have just been completed, unravel this problem by measuring the dielectric constant $\varepsilon_{yy}$ as a function of $T$ and $H$. In the ferroelectric smectic C*-phase the tilt of the long molecular axis and the in-plane spontaneous polarization precess around the normals to the smectic layers as one goes from one smectic layer to the other. The helix disappears for large enough $H$ fields and the polarization directions become uniform in space. This critical field $H_c$ is temperature independent in the theoretical models which have assumed a constant amplitude displacement.

The magnetic field dependence of the dielectric constant close to $H_c$ are in qualitative disagreement with the Landau-de Gennes model of the unwinding of the helix. However, far from $H_c$, the model is in agreement with the experiment. There is a smearing out of the transition resulting in a finite value of the dielectric constant at $H = H_c$. This is in contrast to predictions, but may be explained by analogy to a commensurate to incommensurate transition in a "dirty" ferroelectric. There, impurity pinning of phase solitons results in metastable states where the phase soliton differs from the equilibrium value.

The observed smearing out of the C*-C transition has a hysteresis. Thus going from C* $\rightarrow$ C, $H$ increasing, was not the same when the field was reversed, C $\rightarrow$ C*. In the reverse direction, there is even a peak in the dielectric constant which once again is analogous to impurity "pinning" in a dirty ferroelectric. The nature of the metastability and the unwinding process is still under further investigation.

There are other projects of a fundamental nature taking place, too numerous to mention but I should like to close by mentioning some projects in applied physics. There is a considerable amount of interest in the application of magnetic fields in industry and medicine. We have an extremely productive programme on aspects of High Gradient Magnetic Separation (HGMS) and particle aggregation in magnetic fields with M.R. Parker (University of Salford, England). There are as well a wide variety of industries and government sponsored laboratories in the Netherlands who use our facilities and expertise in exploratory studies using HGMS and other magnetic separation techniques. Recently, we have started testing multifilamentary $Nb_3Sn$ wire for critical current *vs.* field characteristics. This information is required for the various laboratories and manufacturers of superconducting wire who plan to construct magnets or pass this information on to their clients. Not everyone has a 25 or 30 T magnet in their laboratory to test this sort of thing!

## *European Who's Who in Molecular Beams*

Following a suggestion made at the EPS sponsored 9th International Symposium on Molecular Beams, held at Freiburg from 13 to 17 June 1983, the organizing secretary, H. Haberland has put together a first edition of a *European Who's Who in Molecular Beams*.

It contains 198 names of research workers in universities and national institutes classified under country and group leader, the entries including full addresses and, what are so valuable, telephone and often telex numbers. In addition, there is a description of the research programme under way and references to recent publications.

This modestly produced A5 publication of 48 pages will be much appreciated by those in and close to the field. Copies have already been sent to groups who responded to the original enquiry; further copies may be obtained free of charge on request from

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Following the signing of the agreement by the Hungarian Deputy Prime Minister on 8 November 1984, the last hurdle to establishing a Supplementary Secretariat of the EPS in Budapest has been overcome. This will formally come into operation from 1 January 1985.
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The provisional Board of the Optics Division met in Stuttgart in May and again at ECOOSA — the joint meeting of the **Optics** and the **Quantum Electronics Divisions** held in Amsterdam in October — at which a draft constitution for the new Division was approved. This is being submitted to the Executive Committee this month (November).

The main aim of the Optics Division has been defined as constructing a programme of conferences and other meetings, such as summer schools, on both pure and applied topics to include electro-optics and optical engineering in Europe. Great efforts will be made to harmonise all relevant activities in Europe and to bring a greater sense of community into this area of physics. The joint meeting in Amsterdam was a significant beginning — but more of this in a future issue.

### *Senior Physicists*

Retired Members of EPS are reminded that they are entitled to membership at half the normal fee. Those who qualify for the reduction should inform the Secretariat when paying their dues in response to the circular they will shortly be receiving.

## End of a Legend

To many who have studied physics during the past half century, Dirac has been a name to reverence along with those of his compatriot Newton and the other giants who changed the face of physics during the first third of this century. To a privileged few, he was an unforgettable teacher during his many years in Cambridge. He died on 20 October at the age of 82 in Florida.

Whereas Einstein was a world-renowned figure, treated during his visits abroad with the same celebrity publicity as stars from another *monde*, Dirac went through life shunning this wider recognition. His Nobel Prize awarded in 1933 and shared with Erwin Schrödinger was essentially for the equation uniting relativity and quantum mechanics. It predicted the existence of antimatter, notably the positron (discovered in 1932 by C.D. Anderson) but this was just one of his many penetrating contributions to physics made during an exceptionally productive life of research. The finest tribute to his memory would, no doubt, be the discovery of the magnetic monopole; for that, we must wait and see.

Dirac had been an Honorary Member of EPS since 1981.

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