THE GENERATION AND USE OF PULSED MAGNETIC FIELDS

Fritz Herlach, Institute for Nanoscale Physics and Chemistry (INPAC), Katholieke Universiteit Leuven, Leuven (Belgium)

ABSTRACT

The generation and use of pulsed magnetic fields are surveyed from the very beginning with the work of P. Kapitza. The survey is focused on fields in the megagauss range, including non-destructive fields above half a megagauss where the development is now aimed at approaching the 100-tesla limit. In the open literature, megagauss fields were first reported from an experiment with a capacitor-driven single turn coil. This was followed by explosive-driven magnetic flux compression that consistently generates the highest fields. Electromagnetic flux compression was developed from a modest beginning into a research instrument. By far the largest part of scientific research in megagauss fields was accomplished with the single turn coil after it had been developed into a reliable and practical research instrument. The potential for future development of the different techniques and of some novel techniques is indicated.

SURVEY AND ORDERS OF MAGNITUDE

This is a review on all aspects of generating pulsed magnetic fields. Since the author has participated in the development of most of the different techniques almost from the beginning, the review will reflect his preferences that are characterized by the design of uncomplicated, reliable devices and by a straightforward theoretical treatment that is in balance with experimental uncertainties. Only key references are given, more details and references can be found in a recent review[1] and a series of books[2], and of course in the proceedings of all megagauss conferences (see table 1 below for topics).

The highest steady-state magnetic field available at present is 45 T, generated by a large hybrid magnet. It is unlikely that this will be extended beyond 50 T in the foreseeable future. Pulsed magnets can generate much higher fields at a fraction of the cost. With a view to experiments, a pulsed field is clearly defined by the fact that no adjustments of the experimental apparatus can be made during the pulse – this also applies to the so-called "quasi-stationary" magnets. With the many different pulse shapes that can be generated, the overall pulse duration is only a rough criterion; more specifically the rise time, a flat top or the time the field is above a given percentage of the peak value, and the decay time (or the time constant in case of exponential decay) ought to be quoted. For flux compression experiments, it is the slope of the final steep field increase that counts. An ultra-strong magnetic field is defined by a field strength that inevitably destroys the current-carrying structure needed for its confinement. Considering the mechanical strength of currently available materials, the limit between destructive and non-destructive fields with feasible dimensions is in the vicinity of 100 T, corresponding to a magnetic stress of 4 GPa. The term "semi-destructive" can be applied to the single turn coil technique where the coil is destroyed but the sample and cryogenic equipment survives. Non-destructive magnets are now mostly made according to the Leuven design with optimized internal reinforcement by fiber composites.

978-1-4244-2062-9/08/$25.00 ©2008 IEEE

The pulsed magnet is an elegant research instrument in the true tradition of experimental physics where the scientist builds his own advanced instrument. It is efficient in the spirit of Buckminster Fuller's recommendation "do more with less!". The range covered by pulsed magnets is large: non-destructive magnets are used below 50 T where space and circumstances do not permit the use of a large dc magnet; above 50 T they are the only solution. A most ambitious and elusive goal is to achieve 100 T eventually. Pulse duration is between 1 ms and up to a second which requires energy from 10 MJ upwards, and bore size is typically of order 20 mm. The destructive single turn coil covers the range between 100 T and 300 T for convenient experimentation as the sample is not destroyed; bore size is between 3 and 15 mm. Sample destruction begins to occur in the range between 250 and 300 T. The pulse duration is a few microseconds including the trailing part of the pulse. Flux compression provides magnetic fields only on the leading edge of the pulse with typical final rise times of a microsecond or less, and sample destruction shortly after peak field is inevitable. Electromagnetic flux compression now generates reproducibly 600 T with a final diameter at probe destruction of order 5 mm; the technique could be aimed at obtaining 1000 T. Explosive-driven flux compression now generates 1000 T reproducibly in a similar diameter and has been used in a number of experiments; the record is 2500 T with a very big and sophisticated explosive charge.

FROM THE VERY BEGINNING TO THE MEGAGAUSS CONFERENCES

The development of pulsed magnets was started up with a flourish by P. Kapitza[3]. Like most designers of pulsed magnets, he was a great optimist. In 1924, he reported a field close to 50 T in a 1 mm bore from his lead acid storage battery, and was optimistic about obtaining 200 to 300 T if sufficient financial means became available, using for the first time the term "megagauss". He obtained big funding and built his famous flywheel-alternator after coming to the conclusion that the lead acid battery was not practical. In 1927, he had obtained 35 T and expected to obtain 90 T in a 5 mm bore. Although he was an experimental genius, he could not realize this dream that came true only three decades later with destructive techniques. However, he performed a number of remarkable experiments on magneto-resistance, magnetization, magnetostriction, Zeeman effect and particle tracks. To fully appreciate his achievements, it must be kept in mind that no electronic recording instruments were available at that time.

The first report on generating a magnetic field exceeding 100 T came in 1957 from Furth *et al*[4] who used a thick-walled single turn coil on a rather modest capacitor bank with a mechanical switch. This was not followed up for several years. Interest was then generated by Fowler *et al*[5] who reported the generation of fields in excess of 10 megagauss by means of explosive-driven flux compression. In this period, there was much optimism regarding controlled nuclear fusion, with a kind of gold-digger mentality. Many prominent members of that community believed that only a good new idea was needed to pave the way towards a fusion reactor, and many novel experiments were conceived beginning with giving them a fancy name. One of the more colorful characters was Linhart who believed in the quick realization of an unconventional fusion reactor based on high-density plasma. He was appointed as the head of the thermonuclear fusion development of the Euratom with a relatively small group at the Frascati laboratory of the Italian CNEN (Comitato Nazionale per l'Energia Nucleare). Three experiments were pursued: one (called MIRAPI) was the electrical implosion of a ring of plasma created from a powder, the other two were plasma compression by megagauss fields, either generated by electromagnetic implosion in z-geometry (MAFIN 1) or by high explosives (MAFIN 2). Together with Heinz Knoepfel, the author pursued the development of explosive-driven flux compression, inspired by the work of the Fowler group. Starting in 1962, the required techniques were developed from scratch with the aid of private industry. A small bunker with a capacitor bank was built, explosive devices were developed using high-speed photography, and eventually the first flux compression experiments were on the firing table (we had kind of misunderstood the term and built a "real" table made from steel – the first one collapsed after a few shots but then we built one that was strong enough). After a series of trials with disappointing results, Max Fowler was invited and indeed not long after his arrival the first successful experiment was carried out. Max also gave invaluable help for improving the safety of our "amateur" work with explosives. From then on, there was a slow but steady development focused on the development of reliable flux compression devices[6]. A peak field of order 400 T could not be exceeded for some time, but with a simple device using a relatively small amount of explosive and a high initial field, very reproducible performance up to 600 T was finally was achieved and "field turnaround" was consistently observed i.e. the field went through a clear maximum at the peak but the probe was always destroyed shortly afterwards. This will be explained with more detail in a following section.

We suspected that there were other groups doing similar work in military establishments, so one day Heinz suggested to call a megagauss conference for "beating them out of the bush". After much discussion and preparation, the first megagauss conference[7] was held at Frascati in 1965 (Fig. 1), including the successful demonstration of a flux compression experiment at the Colleferro firing site that was built specifically for the purpose of conducting flux compression experiments. This fairly large facility had been designed and built after gaining experience at the small bunker. Although not everybody came out of the bush yet, the conference served its intended purpose and there were lively discussions on the feasibility and reproducibility of explosive-driven flux compression. The biggest surprise was the arrival of 8 abstracts from the Sacharov group in Russia. Unfortunately, our colleagues from Russia were in the end not allowed to come; the publication of their work in Russian Journals[8] may have been a consequence of the conference. As a substitute, the son of P. Kapitza was sent to attend the conference and to eagerly take note of the presentations.

Figure 1. Participants of the first megagauss conference. Third from right is J.G. Linhart, left (with the white jacket) J. van Montfoort, the engineer who made essential contributions to building the new facility and to the running of the conference.

Although the dialogue between the groups engaged in explosive-driven flux compression continued, it took 14 years until P. Turchi organized the second megagauss conference[9] and thus started up the series. Since then, megagauss conferences were held in 1983 (Novosibirsk), 1986 (Santa Fe), 1989 (Novosibirsk), 1992 (Albuquerque), 1996 (Sarov), 1998 (Tallahassee), 2002 (on a boat from Moscow to St. Petersburg), 2004 (Berlin) and 2006 (London). The first conference had been aimed at the generation of megagauss fields and their application to experiments in physics. At the 1986 Santa Fe conference, the range of topics was extended to non-destructive fields above half a megagauss, and efforts were made to attract more contributions on science in ultra-strong fields. The percentage of high-field related topics at all conferences is shown in table 1. The abbreviations in the table refer to explosive-driven flux compression (XFC), electromagnetic flux compression (EMFC), flux compression by shock waves (SWFC), capacitor-driven single turn coil (CST), and non-destructive (N-D); "special" refers to techniques such as involving lasers or "force-free" coils, "Fusion" to papers related to nuclear fusion (this category involves pulsed power and is generally not so well defined). "Science" includes all experiments and techniques related to experimental physics. Papers on pulsed power and defense-related topics are not listed in the table.

Table 1 Percentage of papers on **high-field related** topics presented at MG conferences

MG -	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	2006
	1964	1978	1983	1986	1989	1992	1996	1998	2002	2004	2006	2006
papers	27	61	65	98	113	127	80	149	148	88	119	90
%												
XFC	52	11	8	3	4	6	10	4	3	2	1	1
EMFC		2	3	2	4	2	3	1	1	1	2	2
SWFC			2	1			3				1	
CST		3	6	3	2	2	5	2	2	2	2	2
N-D		2		3	1	6	3	12	2	8	3	6
special		7	5	3	1	1		1		1	2	2
Science	7	5	3	10	6	9	3	13	7	19	8	14
(Fusion)	7	16	8	5	6	9	13	9	13	3	3	17
total %	67	46	34	31	23	35	38	42	28	38	20	44

BASIC PRINCIPLES OF GENERATING A MEGAGAUSS FIELD

The generation of a megagauss field is a complex process involving non-linear functions. Sophisticated computer programs have been developed for the calculation. However, within the large uncertainties inherent in megagauss generation, the following straightforward and simple estimate is adequate. Any magnetic field is confined within electrical conductors that carry the current. A field of 100 T corresponds to a linear current density of 0.8 MA/cm; the energy density is 4 kJ/cm^3. The pulse duration is short because the energy has to be concentrated in the field volume before it is expanded due the magnetic stress. Therefore the current is confined to a thin "skin" layer at the conductor surface facing the field. Joule heating will cause melting, vaporization and ionization of the skin layer. The magnetic stress is transmitted to the conductor within the skin layer, resulting in compression of the conductor material. Depending on the slope of the applied pressure pulse, a shock wave will form at a certain distance from the surface. In approximation, the surface will then recede from the magnetic field at the particle speed associated with the shock wave. This is related to the equation of state of the conductor material by a simple empirical function with two parameters[1]. The velocity of the shock wave comes into play for finite wall thickness of the conductor. Until the shock wave reflected at the outer surface returns as a rarefaction wave to the inner surface, seen from this surface the conductor appears to be infinitely thick. Due to the finite conductivity of the conductor material, it is not a perfect barrier for the enclosed magnetic flux. Flux leaks into the conductor material at a speed that is called the Alfven velocity in plasma physics and that we may call the flux diffusion speed; it is given by the ratio of electric to magnetic field. The expansion of magnetic flux enclosed by the inner surface of the conductor is thus determined by the sum of the particle speed and the flux diffusion speed. Normally the particle speed is much larger than the flux diffusion speed and thus it is the dominant factor. Straightforward experimental proof will be presented below. Regarding heat conduction, the process can be regarded as adiabatic, but heat is carried away by radiation from the surface at a rate that is proportional to the 4^{th} power of the temperature.

EXPLOSIVE-DRIVEN FLUX COMPRESSION

Cylindrical implosion

For generating the highest fields, devices with cylindrical implosion are used. Magnetic flux is introduced into a metallic “liner” (so called because it is a lining to the explosive charge) and this is imploded at a speed that must be much higher than the flux diffusion speed. Technically this poses two challenges. One is the system of explosive, detonators and liner that must provide a regular implosion; the other is the coil that generates the initial field. The rise time of the initial field must be sufficiently long with respect to the time constant of a seamless liner in order to allow introduction of the field into the liner. Because it is destroyed in the experiment, the coil system should not be too elaborate, on the other hand it should not move until its peak field is reached. The coil system should of course not interfere with the high precision explosive charge, and in any case a compromise has to be made. In the early experiments, a coil pair was mounted on both sides of the explosive charge, and the liner had an insulated slot to allow the introduction of the initial field in a short time to avoid movement of the coils. This provided relatively high initial fields but the implosion symmetry was disturbed by the slot even if it was made very thin and cut at an angle, therefore this arrangement did not give reproducible results. At Frascati, stainless steel liners were used that have a longer time constant and thus are less efficient for the flux compression because of the higher resistance. The radial extension of the explosive charge (made from plastic molded or sheet explosive) was limited to provide just enough energy for the implosion, and the coil was made to closely surround the explosive. Based on the Frascati design, at the Illinois Institute of Technology a small elegant device (Fig. 3) was developed[10]; it generated 400 T reproducibly. These devices have only one detonator, the detonation front is very regular and travels in the axial direction; this results in implosion of the liner in the shape of a cone, with the point where peak field occurs moving along the axis. The fairly high initial field and good implosion symmetry allowed reproducible observation of field turnaround for the first time. A field trace from a Frascati device is shown in Fig. 2, together with the analysis[11]. This is from a time when analysis was done with slide rule, pencil and paper. However, the results are still valid and useful today as an example for the evaluation of a flux compression experiment[12]. From a simple theory inspired by Sacharov, the movement of the inner surface of the liner was calculated. In the early phase of the implosion, the inner radius was also determined from framing camera pictures and good agreement was found. It came as a revelation that the inner surface turned out to be close to the pick-up probe at the time of the field maximum. This is still the best method for determining the critical final speed of the inner surface shortly before peak field is reached[12]. In particular, the destruction of the probe that occurs shortly after the field maximum ("field turnaround") could be naturally explained, without the need to assume instabilities that were indeed never observed in high-speed photography. At the field maximum, the inner surface of the liner is still moving at a speed that is equal in absolute value to the flux diffusion speed, therefore it runs into the pick-up coil probe shortly after the maximum. In Fig. 3, the peak field of all experiments for which data on the implosion speed are available has been plotted as a function of the speed. This is compared to the Hugoniot curve for copper in the form that gives the particle speed in the shock wave associated with the magnetic stress. It is remarkable that all experimental points are close to this curve; the points for stainless steel liners follow the Hugoniot but are lower because of the higher flux diffusion speed. This confirms the simple argument given above for the peak field in relation to the implosion speed.

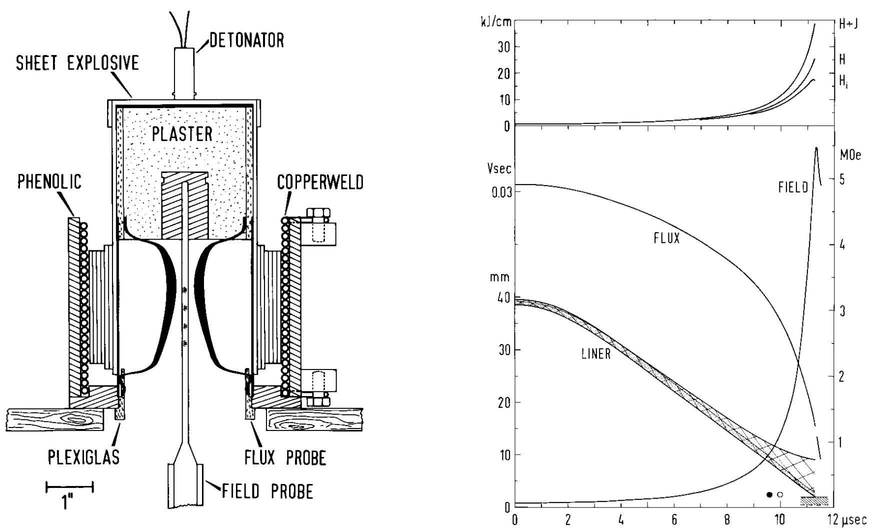

Figure 2. Left: The IIT flux compression device[10]. The liner is shown in the initial state and during compression (from flash X-ray). Right: Analysis of a Frascati flux compression experiment with stainless steel liner[11]. In the liner, characteristics (lines showing propagation with the speed of sound) and the skin depth are shown. The upper frame shows energies: magnetic inside liner, magnetic total, magnetic plus Joule heat

At Sarov (former code name Arzamas-16), a very efficient system for generating a high initial field was developed, combining the function of the liner and the initial field coil in the form of a winding of many thin insulated copper wires in parallel[13]. This is transformed into a conducting cylinder when it is hit by the detonation wave. The implosion turned out not to be very stable and symmetrical; it could be stabilized by "cascades" which are cylinders made from thin insulated copper wires strung in the axial direction (later, the use of metal powder was investigated as well). When the imploding liner hits such a cascade, it becomes conducting and unites with the liner, stabilizing the implosion. This design generated 1000 T for the first time reproducibly and has been used for experiments at both Sarov and Los Alamos in the "Kapitza" and "Dirac" series of experiments with guest researchers from many countries. A disadvantage of the cascades is that they generate electrical noise that can severely disturb electrical measurements. A very large device with a two-stage explosive system has generated fields up to 2500 T; because of the complicated design and the large amount of explosive only very few shots have been accomplished.

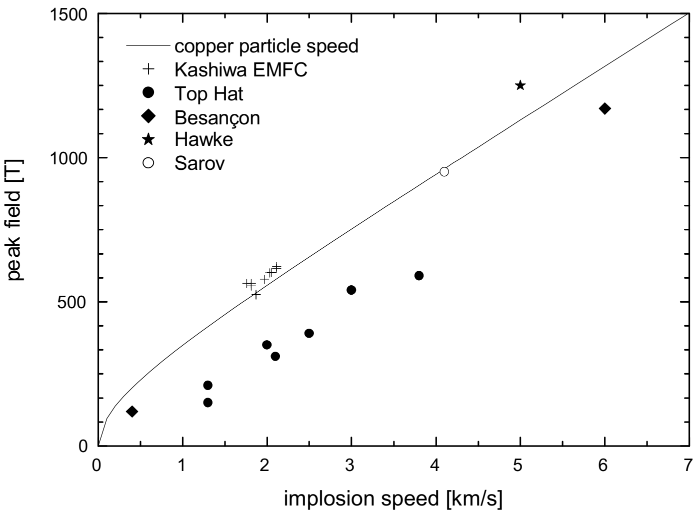

Figure 3. Peak field versus measured final implosion speed for a variety of flux compression experiments. The line shows the particle speed of a shock wave in copper.

Generators supplying an energy pulse to a load

Three basic configurations have been used for generating a pulse of electrical energy by explosive-driven flux compression. The first is the "bellows" device developed at Frascati that uses the implosion of flat plates in the shape of a bellows to squeeze the compressed flux into a massive single turn coil. The separation of the coil from the explosive introduces a time delay of the destruction such that the field pulse generated in the coil extends into the trailing slope. This type of device was used for physics experiments in the lower megagauss range at Los Alamos. The most common explosive-driven generator of pulsed electrical power is a helical winding containing the charge enclosed in a liner that is coaxial with the helix, sometimes with a coaxial final stage. The explosive is detonated along the cylinder that expands in the shape of a cone. By changing the pitch of the helix, the pulse shape and the efficiency can be affected. A most powerful compact device is the disc generator where the explosive/liner system is arranged as a stack of discs. This is now used for plasma compression experiments that may have a better chance than the original experiments proposed by Linhart. Many varieties of pulsed power generators have been presented at the megagauss conferences, in fact together with their applications they make up for the majority of papers.

ELECTROMAGNETIC FLUX COMPRESSION

Electromagnetic flux compression (EMFC) in theta-pinch geometry was introduced by Cnare[14] with a thorough study, including an elegant and straightforward theoretical treatment. This was followed up at IIT (Chicago) and used for a successful demonstration experiment at the Stanford Linear Accelerator. Alikhanov demonstrated that EMFC also works well in z-pinch geometry. At the Institute for Solid State Physics (ISSP) at the University of Tokyo, EMFC was developed into a research instrument[2]. The final instrument that is now installed on the Kashiwa campus is a heavy installation consisting of a 5 MJ capacitor bank for the implosion and a 1.5 MJ bank for the initial field. In theta-pinch geometry, the driving field is generated by a thick-walled single turn coil made from steel; the feed gap of this coil introduces an irregularity in the implosion that becomes more prominent with increasing liner speed, thus defeating the effort of obtaining a high liner speed. This was observed with flash X-ray at IIT and with an image converter camera at ISSP (Fig. 4). The feed gap effect could be substantially reduced by inserting a flux concentrator with small radial gaps between the primary coil and the liner[12]. This system generated record fields and was used for the first high-field solid-state experiments with EFMC. Recent experiments with a primary coil clad with copper on the inside will be presented at this conference by Kojima.

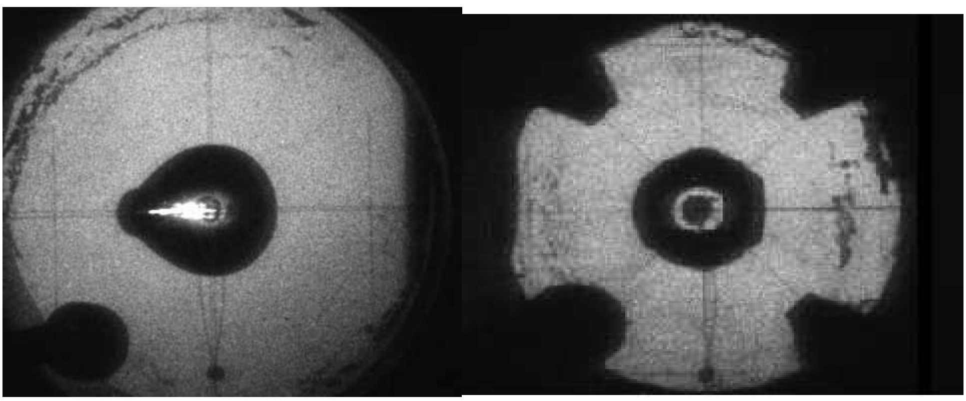

Figure 4. Pictures of the imploding liner in EMFC taken at ISSP with an image converter camera and backlighting. The picture on the right shows the effect of a six-gap flux concentrator inserted between the primary coil and the liner.

THE SINGLE TURN COIL

Several years after the experiments by Furth *et al*[3] (160 T with 24 kJ at 4 kV), megagauss generation by the single turn coil was taken up again; Shneerson obtained 150 T with 222 kJ at 125 kV, thus demonstrating the importance of optimizing experimental parameters . Shearer[15] went to the limits of a thick-walled coil by discharging a 0.82 MJ capacitor bank at 70 kV into a plate with a radial slit, generating 355 T, so far still the highest field ever obtained from a direct capacitor discharge. The Demishev group at the Kurchatov Institute investigated materials with high density such as Tantalum that have Hugoniot curves with lower particle speed. Higher peak fields were achieved but generally it was found that the gain is less than expected. Forster and Martin[16] demonstrated that a thin-walled coil generates the field most efficiently with a capacitor discharge at very low inductance (0.9 nH) and resistance (0.5 mΩ); they obtained 260 T using only 63 kJ at 15 kV. All early coils had a bore of order 3 mm. Herlach and McBroom[17] developed this concept into a practical research instrument, using mass-produced coils in a hydraulic clamping mechanism. With moderate values for inductance (14 nH) and resistance (6 mΩ), up to 200 T were obtained with 55 kJ at 20 kV with different sizes of the thin-walled coils. This was first used for an experiment on magnetic Bremsstrahlung at the Stanford Linear Accelerator and later for the first experiment on cyclotron resonance in semiconductors with infrared radiation in a megagauss field. The most important discovery was that a sample placed in the megagauss field is not destroyed despite of the violent explosion of the coil. An enlarged copy of the system with 100 kJ at 40 kV and many spark gaps instead of the solid dielectric switch was installed in 1983 at the University of Tokyo[18]; this was conceived as a sturdy user facility and it provided completely trouble-free operation with up to 1 pulse per hour until 1999 when the megagauss laboratory was moved to the new campus at Kashiwa. There two new single turn systems with 200 kJ each were installed with the same basic design, one with the coil axis horizontal at 50 kV and one vertical (for use with a liquid He cryostat) at 40 kV. In 1994, a system with rail gap switches and relatively light collector plates was installed at the Humboldt University in Berlin with 200 kJ at 60 kV. This laboratory has now been closed and the system is moved to the Laboratoire National de Champs Magnétiques Pulsés at Toulouse (LNCMP). All 200 kJ systems generate fields up to 300 T, but it was found that sample destruction occurs frequently in the range between 250 T and 300 T. So far, the single turn coil is the only system that has consistently produced a large amount of excellent results from a variety of experiments in solid-state physics: infrared resonance, optical magneto-spectroscopy, magneto-resistance and magnetization; most of these were done at ISSP and in a miniaturized helium flow cryostat.

NON-DESTRUCTIVE FIELDS

Monolithic coils

Many years after the Kapitza experiments, Shoenberg and Olsen revived experiments with non-destructive pulsed magnets[1]. The Olsen group at Zürich did pioneering work on the magneto-resistance of metals and used some of their small coils directly in liquid helium. Several other laboratories developed experimental facilities for pulsed fields, all using coils with soft copper wire and external reinforcement by steel cylinders. The peak field was typically 45 T. Foner[19] made the breakthrough with a new type of wire specifically developed for high strength: copper with microfilaments of niobium. This moved the peak field up to 68 T and it was a great inspiration for others to engage in the development of coils for higher fields. At the National Institute for Metal Science at Tsukuba, copper wire with silver microfilaments was developed; due to the less complicated fabrication process this was more homogeneous and of high quality. For a number of years, it was commercially produced by the Showa company, but recently fabrication was discontinued. At the Clarendon Laboratory (Oxford), copper wire with a stainless steel mantle was developed as an economical alternative, this has the advantage of a higher resistance ratio (between 300 and 77 K) and high strength at liquid nitrogen temperature. This wire is now also produced at the LNCMP, and it is commercially available from the Bochvar institute at Moscow. That institute also produces copper-niobium wire; Cu:Nb wire with extreme strength is under development at LNCMP.

Development of strong wire is also under way at the IFW Dresden. This still has to be done mostly at research institutions because the required quantities are not sufficient for profitable commercial production. This may change when other applications can be established for these wires, for example in the exploration of outer space.

At Leuven, the author developed an efficient coil design[20] that has now been adopted by most pulsed field laboratories. This is optimized internal reinforcement by insulating fiber composites. Between layers of wire, layers of strong fibers (to be impregnated with epoxy) are wound and the thickness is adjusted such that in each layer the peak stress is approximately the same and close to the ultimate tensile strength. A user-friendly computer program "PMDS" was developed to determine the optimal thickness of the layers and coil performance in general. Originally, S-glass was used, but then the organic fiber Zylon became available with UTS of order 6 GPa. Carbon fiber has similar strength but it causes trouble due to its conductivity; it is useful for inexpensive outer reinforcement. The advantages of this design are easy construction and efficient performance. Fig. 5 shows two examples; one (a) with two different wires and reinforcing materials, and one (b) with soft copper and Zylon composite. This calculation shows the effect of anisotropy: a fiber composite is only stiff in the direction of the fibers and soft in the perpendicular direction. To demonstrate the effect, the calculation has been made for isotropy and for two different values of the perpendicular modulus; 3 GPa is a value that has been quoted for Zylon. Axial compression appears to be essential for obtaining the highest fields.

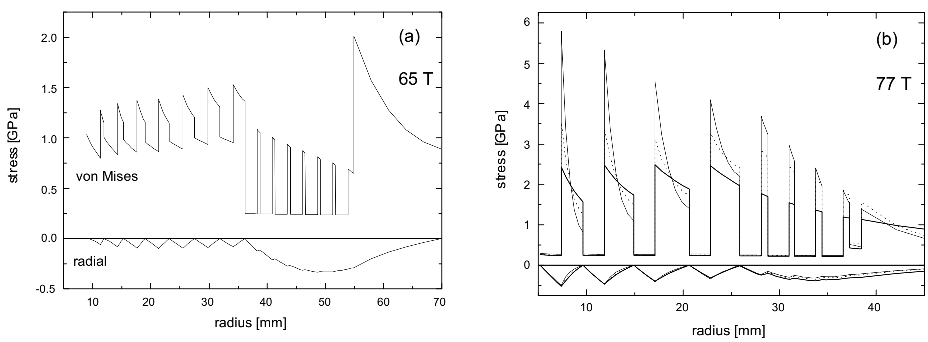

Figure 5. Stress distribution in coils with optimised reinforcement by fibre composites. Left graph (a) is a coil with copper-stainless steel wire and Zylon in the inner section, soft copper and S-glass fiber in the outer section, the outer shell is carbon fiber composite; Right graph (b) shows the effect of the anisotropy of fiber composites in a coil with soft copper wire and Zylon; curves are shown for isotropy at 230 GPa (bold) and for a radial modulus of 10 (dots) and 3 GPa (upper line). This coil failed at 77 T.

Multiple coil systems

Regarding the relation between peak field and stress, a dual coil system does not a priori have an advantage over a monolithic coil. There is a geometrical gain depending on the ratio α of the outer and inner diameter of the coil. For example, a coil with the same materials can support a 50 % higher field when α is increased from the typical value of 5 to 40. Increasing α further does not make much sense because the gain is approximately proportional to the logarithm of α. A coil with a bore of 20 mm and $\alpha = 40$ has an outer diameter of 800 mm, thus it has a large volume and requires much electrical energy. The relatively high resistivity of strong materials calls for short pulse duration in order to avoid overheating. For the high energy required for a big coil, this would require extremely high power that cannot be furnished by a feasible power supply. This is circumvented by a system of two or more coils where the large outer coils are energized by a more conventional power supply with long pulse duration, while the innermost coil is energized by a supply with moderate energy (typically 1 to 10 % of the outer coils) at high power. The usefulness of this concept was first demonstrated in a co-operation of the Leuven and Amsterdam pulsed field laboratories, and an 80 T coil system called ARMS was built and successfully operated in co-operation by a group of European laboratories. It was found that the design of the outer coil is more critical than anticipated; in order to avoid catastrophic failure it has to be conservatively designed and thus it is less energy-efficient. Recent developments of advanced monolithic coils and dual coil systems are presented at this conference by Wosnitza and by Swenson.

CONCLUSION AND OUTLOOK

Explosive-flux compression most probably has reached the limits of feasibility. There is still some potential for further development of EMFC including new techniques such as flux compression in a shock wave generated by impact on a metal powder[21]. The single turn is likely to remain the workhorse for experiments; a substantial increase of the peak field is unlikely. Advanced experimental techniques will be further developed. Regarding pulsed power, there appears to be a revival of Fusion-related research. Nondestructive magnets will be gradually developed towards higher fields with emphasis on true user coils. It will take extreme efforts to extend this up to 100 T, and it is a good question up to which point this will be justified by the potential gain for experiments. An interesting alternative is given by mini- and micro-coils that can generate high fields with very small power supplies and thus provide a high degree of portability. Potentially the highest fields can be generated by inducing an extremely short current pulse in a small coil by means of a high-power laser pulse. At MG-VIII, an entire section was dedicated to this topic, and recently very efficient non-destructive miniature coils were developed[22].

In the past, new insights were usually gained whenever the range of an experimental parameter was expanded. Pulsed magnets have extended the range of magnetic fields by more than two orders of magnitude. A lot of solid and excellent experimental work has been done, but so far no really new fundamental insight has been gained. This remains a challenge for the next generation, and it calls for a realistic assessment along which lines experiments can best be efficiently pursued.

ACKNOWLEDGMENT

While approaching the conclusion of his work as experimental physicist, the author wants to express his deep gratitude to his teachers Paul Scherrer and Wolfgang Pauli. Scherrer inspired us to see the beautiful simplicity of the physics underlying the phenomena all around us, and Pauli admonished us to strive for sincerity and correctness. The author is also indebted to Noboru Miura for his generous hospitality and congenial co-operation, and to Max Fowler for substantial help, advice and lasting friendship. Heinz Knoepfel and in particular Joop van Montfoort were good companions at Frascati.

REFERENCES

1. Herlach F, "Pulsed Magnets", *Rep. Prog. Phys.* 62 (1999) 859-920
2. Herlach F and Miura N, eds., *"High Magnetic Fields: Science and Technology",* three volumes (World Scientific, Singapore 2003-2006)
3. ter Haar D, "Collected papers of P. Kapitza", Vol. 1 (*Pergamon Oxford* 1964), containing "Method of producing strong magnetic fields", *Proc. Roy. Soc*. A105 (1924) 133-52 and "Further developments of the method of producing strong magnetic fields", *Proc. Roy. Soc.* A115 (1927) 658
4. Furth H P *et al*, "Production and use of high transient magnetic fields II", *Rev. Sci. Instrum*. 28 (1957) 949-58
5. Fowler C M *et al*, "Production of Very High Magnetic Fields by Implosion", *J. Appl. Phys.* 31 (1960). 588-94
6. Herlach F and Knoepfel H, "Megagauss fields generated in explosive-driven flux compression devices", *Rev. Sci. Instrum.*. 36 (1956). 1088-95
7. Knoepfel H and Herlach F, eds., *Proc. Conf. on Megagauss Magnetic Field Generation and Related Experiments, Frascati, Italy, Sept. 21-23, 1965* (Euratom, Brussels 1966) 537 pp.
8. Sacharov A D, "Magnetoimplosive generators", *Usp. Fiz. Nauk 88 (1966) 725-34;(Sov. Phys. - Uspekhi 9 (1966) 294-9*
9. Turchi P J, ed., *"Megagauss Physics and Technology": Proc. Second International Conference on Megagauss Magnetic Field Generation and Related Topics*, *Washington, D.C., 29 May - 1 June 1979*, (Plenum Press New York 1980) 683 pp.
10. Herlach F and Kennedy J E, "The dynamics of imploding liners in magnetic flux compression experiments", *J. Phys. D: Appl. Phys.* 6 (1973) 661-76
11. Herlach F, "Flux loss and energy balance in magnetic flux compression experiments", *J. Appl. Phys.* 39 (1968) 5191-204
12. Matsuda Y H, Herlach F *et al*, "Generation of 600 T by electromagnetic flux compression with improved implosion symmetry", *Rev. Sci. Instrum.* 73 (2002) 4288-94
13. Pavlovskii A I *et al*, "Reproducible generation of multimegagauss magnetic fields", in *"Megagauss Physics and Technology"* [9] p. 627-39
14. Cnare E C, "Magnetic Flux Compression by Magnetically Imploded Metallic Foils", *J. Appl. Phys. 37* (1966) 3812-6
15. Shearer J W, "Interaction of capacitor-bank-produced megagauss magnetic field with small single-turn coil", *J. Appl. Phys*. 40 (1969) 4490-7
16. Forster D W and Martin J C, "2.5 megagauss from a capacitor discharge", in *Proc. Int. Conf. ``Les champs magnétiques intenses, leur production et leurs applications"*, Grenoble, 12-14 Sept. 1966, ed. R. Pauthenet, (CNRS Paris 1967)
17. Herlach F and McBroom R, "Megagauss fields in single turn coils", *J. Phys. E: Sci Instrum.* 6 (1973) 652-4
18. Nakao K, Herlach F *et al*, "A laboratory instrument for generating magnetic fields over 200 T with single turn coils", *J. Phys. E: Sci. Instrum.* 18 (1985) 1018-26
19. Foner S, "68.4-T-long pulse magnet: Test of high strength microcomposite Cu/Nb conductor", *Appl. Phys. Lett.* 49 (1986) 982-3
20. Herlach F *et al* "Elements of pulsed magnet design", presented at RHMF2006 and accepted for publication in *Journal of Physics: Conference Series* (IOP 2006)
21. Novac B M *et al*, "A fast and compact θ-pinch electromagnetic flux-compression generator" *J. Phys. D: Appl. Phys.* 37 (2004) 3041–55
22. Ohmichi E and Osada T, "Pulse micromagnet for practical high-field measurements", *Rev. Sci. Instrum.* 76 (2005) 076103, 4 pp.