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# Beyond 100 Tesla: Scientific experiments using single-turn coils

## *Au delà de 100 Tesla : expériences scientifiques dans des bobines mono-spires*

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ABSTRACT

Current opportunities and recent examples for research in magnetic fields well above 100 T using single-turn coils are discussed. After a general introduction into basic principles and technical constraints associated with the generation of Megagauss fields we discuss data obtained at the LNCMI Toulouse, where such fields are routinely used for scientific applications.

RÉSUMÉ

Nous discutons des perspectives et des exemples récents de recherche sous champs magnétiques intenses bien au delà de 100 T obtenues à l'aide des bobines mono-spires. Après une introduction générale des principes de base et des contraintes techniques associées au champs Megagauss nous présenterons des données mesurées à Toulouse ou ce genre de champs sont utilisés de façon régulière pour des applications scientifiques.

## 1. Introduction

The generation of high magnetic fields in electromagnets is fundamentally limited by the effects of thermal dissipation and magnetic pressure. The dissipation problem can be addressed in two different ways, depending on the timescale of the magnetic field. Whereas for stationary fields adequate cooling is mandatory, pulsed field techniques rely on the heat capacity of the magnet to buffer a limited amount of thermal energy generated over a short period of time.

It is less well known — though not surprising — that two alternative approaches, one static and one dynamic, also exist for containing magnetic pressure. On a sufficiently short timescale, the mechanical inertia of a magnet can impede its deformation by an applied magnetic pressure more efficiently than any reinforcement structure. The latter fact has given rise to a separate category of field generation techniques. At the time of writing, these so-called Megagauss or destructive pulsed techniques represent the only option for generating fields well above 100 T in a macroscopic volume.

The intrinsically short duration of destructive pulsed fields — typically a few microseconds — represents a formidable challenge for implementing scientific experiments. The advent of fast electronics and opto-electronics has nevertheless rendered Megagauss fields increasingly accessible for applications in areas such as solid state spectroscopy. The purpose of the

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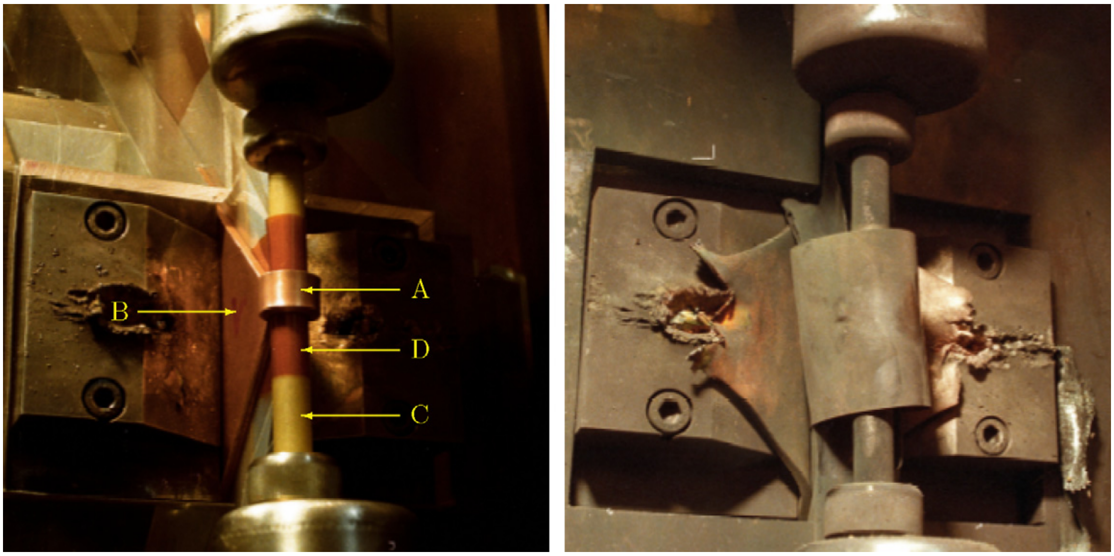

**Fig. 1.** Single-turn coil before and after a shot. On the left the coil (A) with the current-feed flanges (B) and a plastic tube (C) that contains the sample holder and cryostat are shown. The inside of the coil and feed flanges is insulated with a strip of polyimid film (D). On the right the ensemble is shown after the shot. The feed flanges are bent open and the insulation strip has popped up. Note the impact traces that are well confined to the mid-plane of the coil.

present paper is to review the general conditions under which experiments can be performed in Megagauss fields and to demonstrate the quality of measurements performed with state-of-the-art equipment. Our discussion will mainly focus on results obtained with single-turn coils whose principal advantage lies in the fact that the destruction of the magnet does not affect other experimental equipment. Repeatable measurements using the same sample and setup are therefore possible up to fields of about 200 to 250 T.

## 2. Megagauss magnetic field generation

The simplest way to generate Megagauss fields is to rapidly inject a strong current into a primitive coil that consists of a single winding. The current gives rise to a magnetic field that manifests as magnetic pressure acting on the coil. In the Megagauss range this pressure exceeds by orders of magnitude the tensile strength of the conductor material and the coil thus behaves as a loose ensemble of segments that are gradually accelerated. A fairly accurate analytic expression for the coil disintegration can therefore be obtained by solving the equation of motion for a single conductor element being subject to, for example, the pressure of a sinusoidal magnetic field. Based on reasonable assumptions for the coil size and material one thus finds that in order to avoid a premature expansion of the coil – this would obviously lower the field – the risetime must be of the order of microseconds.

With reported maximum fields in the 300 to 350 T range [1–3], single-turn coils are less powerful than flux compression techniques [4] as far as pure field strength is concerned. Their principal importance rather lies in the fact that they represent the only known technique capable of generating magnetic fields well above 100 T without causing damage inside the experimentally useful volume. The semi-destructive operating regime of single-turn coils holds up to about 250 T and is a simple consequence of the fact that the prevailing electromagnetic forces direct fragments away from the coil axis. Above 250 T single-turn coils become increasingly destructive as the applied current starts to vaporize large amounts of conductor material from the inner surface of the coil [3]. Vapor that cannot escape along the coil axis subsequently damages equipment inside the bore.

Fig. 1 shows images taken before and after a shot with a single-turn coil. The coil is attached to triangular current-feed flanges that are connected to the generator with the aid of a hydraulic press. Coil and feed flanges are cut out of a 3 mm thick copper plate before being bent to their final form. Coils are typically dimensioned such that their diameter equals their axial length. The use of a hydraulic press is motivated by the fact that it permits a rapid replacement of the coil after each shot.

Fig. 2 shows typical field profiles obtained with single-turn coils featuring various diameters. The kinks in two of the traces are due to failures of the inductive field probe. The disintegration of the magnet remains practically invisible as the rupture triggers arcs and the current simply continues to flow. The fact that both the up and down sweeps of the field can be observed represents a considerable advantage as it permits an immediate testing of the reproducibility of experimental data. The latter fact will be discussed in more detail in the following section.

In the past, various efforts have been undertaken to improve the performance of single-turn coils. The use of more massive conductor materials than copper thus permits a moderate field gain, albeit at a substantial increase of cost [2].

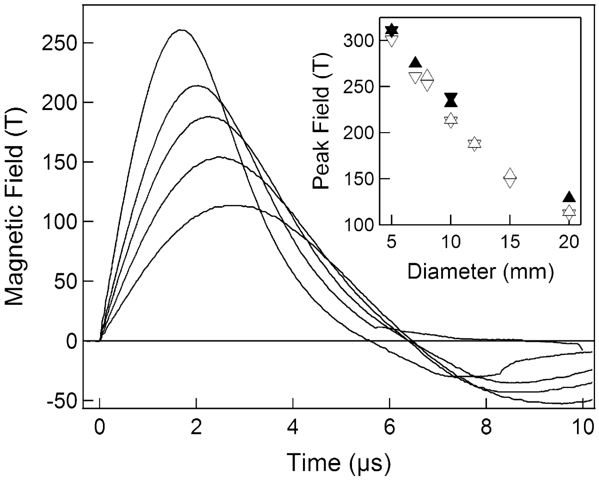

**Fig. 2.** Magnetic field pulses obtained with single-turn coils featuring inner diameters of 8, 10, 12, 15 and 20 mm. Whereas the peak field decreases with diameter the pulse duration is clearly prolonged. Coils diameters down to 8 mm can be used to accommodate scientific experiments requiring low temperatures. The inset shows more peak fields obtained with different charging voltages and smaller coil diameters. In a 5 mm coil a field of 311 T has thus been obtained.

Thick-walled coils have likewise been tested but lead to massive destruction. This is a consequence of the fact that the applied current is primarily confined to the inner surface of single-turn coils. Forces thus start as shock-waves propagating from the bore into the coil body where they are reflected. As a consequence fragments may be projected into the bore rather than away from it.

A notable recent development concerns the use of giant single-turn coils at the ISSP Tokyo that can produce fields around 100 T with much longer pulse duration. The Tokyo group has thus been able to measure for the first time spectrally resolved optical data with a single-turn coil [5].

## 3. Experimental conditions in Megagauss fields

The successful implementation of scientific experiments in Megagauss fields obviously depends on their compatibility with the inherent field sweep rates exceeding $10^8$ T/s. Several factors have to be considered in this respect: the speed of detectors and data acquisition systems, the effect of induced voltages on samples and equipment, and the intrinsic time constants of the investigated materials.

Transient recorders featuring sampling rates of $10^9$ S/s with vertical resolutions of up to 12 bit are nowadays commercially available. A technical challenge rather arises from the necessity to implement preamplifiers and detectors providing sufficient analogue bandwidths while being protected against electromagnetic perturbations.

Induced voltages generally restrict the choice of materials for cryogenic equipment and sample holders all of which must be insulating. Cryostats that allow temperatures between 4 K and room temperature have nevertheless been successfully developed.

Likewise, experimental techniques must be wireless or based on carefully compensated arrangements. Pick-up coils for magnetization measurements, for example, are compensated winding by winding to avoid the build-up of voltages that would otherwise provoke the failure of electrical insulations. On the other hand, optical experiments are ideally suited for Megagauss fields since sources and detectors can be remotely located and the small size of the coils guarantees easy access.

Other than experimental equipment, induced voltages tend to affect conducting samples via eddy currents and their various side-effects. Conducting samples are thus subject to the same types of constraints as pulsed field coils, namely the effect of magnetic pressure and dissipation. In addition, one has to consider a partial screening of the applied field that can give rise to experimental errors and the effect of a radial Hall-field that shifts carriers between the center and the edge of the sample [6]. Without going into detail, we note that all these effects essentially depend on $\partial B/\partial t$ rather than $B$ itself and hence can be identified by carefully examining differences between experimental data obtained during the up and down sweeps of the field. If necessary, the problem can then be reduced by consequently minimizing the size of the sample.

At least one case has also been reported where the µs-duration of Megagauss fields is in conflict with an intrinsic time constant — the spin-lattice relaxation time — of the investigated material [7–9]. While in such a case Megagauss fields cannot be used for measurements under quasi-equilibrium conditions they, nevertheless, represent a powerful tool to study the underlying dynamics. In particular for measurements not requiring the highest possible fields one has the option to vary the pulse duration by using different coil sizes, or to apply an alternating field as shown in Fig. 3.

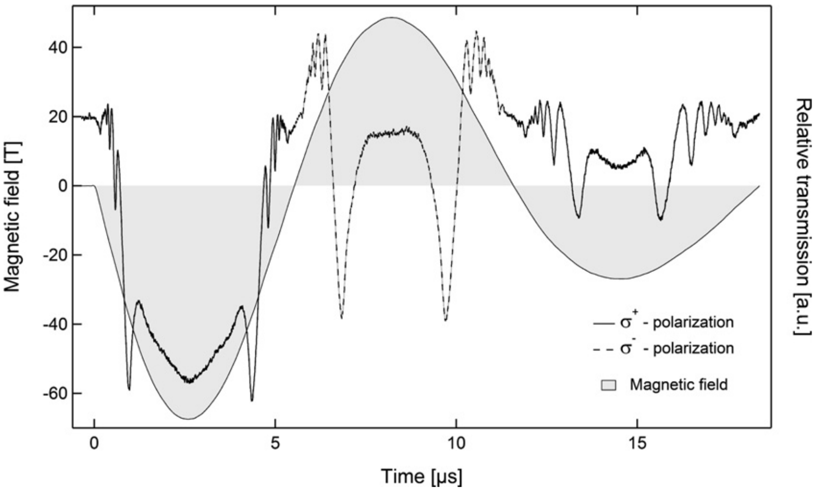

**Fig. 3.** Single shot acquisition of both circular polarizations in the infrared transmission of graphite. The optical trace exhibits perfect correspondence between parts recorded during the up and down sweeps of each field oscillation as well as during the first and third half-waves. By comparison the transmission changes characteristically on the second, positive half-wave as the sense of the circular polarization is effectively reversed. Note that data obtained during the third half-wave misses one resonance due to the diminished field yet resolves all other resonances much better. The measurement was performed at 300 K with a CO-laser producing radiation at 229 meV.

## 4. Experimental results

The first Megagauss generator with the express purpose of conducting scientific experiments was built in Chicago in 1973 and operated for a couple years [10]. At the ISSP Tokyo, experiments using single-turn coils as well as electromagnetic flux compression have then been performed on a regular basis since the early 1980s. After that, generators using single-turn coils have also been constructed at the NHMFL Los Alamos and at the Humboldt-University Berlin. The latter installation has been moved to Toulouse where it has been in regular operation since 2010. In the present section we present results from the first successful research projects that have been undertaken there. For more information on results obtained in Tokyo, Los Alamos and Berlin the reader is referred to several review articles [11–13] as well as more recent publications [5,14,15].

So far experiments in Megagauss fields at the LNCMI Toulouse have been primarily concerned with optical properties of epitaxial graphene and exfoliated graphite. We have thus addressed three basic problems, namely the origin of the electron-hole asymmetry and the band structure far from the Fermi energy in graphite and the difference between graphite and epitaxial multi-layer graphene. In the following we discuss a small part of our measurements in order to demonstrate the high quality and usefulness of optical measurements in Megagauss fields.

Fig. 3 shows a typical example of original data obtained with graphite during a single shot at comparably low magnetic field. As the field oscillates repeatedly the recording demonstrates both the remarkable reproducibility of the measurement and the difference between left- and right-hand circular polarizations. The overall transmission level thus has characteristic differences between positive and negative half-waves of the field as a consequence of the effective change of polarization. Conversely, the up and down sweeps during each half-wave of the field are in perfect agreement.

The upper part of Fig. 4 shows the optical data already displayed in Fig. 3 plotted against the recorded magnetic field. In the lower part data obtained at higher fields under otherwise identical conditions is included to exhibit an additional high field resonance. The combination of high and low-field shots serves to verify the reproducibility of all observable features and to improve the resolution of low-field structures that — while being generally narrower — are exposed to the highest field-sweep rates.

The resonances in Fig. 4 originate from transitions involving different Landau levels in the $E_{3+}$ and $E_{3-}$ bands at the K-point of graphite. Resonances on the left- and right-hand side of the figure correspond to $(n \rightarrow n+1)$ and $(n+1 \rightarrow n)$ transitions and — for a given value of $n$ — are slightly shifted with respect to each other. The shift reflects an electron-hole asymmetry and has been attributed in a recent publication to the free electron kinetic energy term [16]. Unlike other interactions that change sign between valence and conduction bands the free electron kinetic energy is always positive and hence introduces an additional asymmetry in an otherwise symmetric pair of bands.

Fig. 5 shows an example of measurements performed at higher radiation energies. In addition to transitions between the $E_{3+}$ and $E_{3-}$ bands that account for the dominant part of the spectrum we now observe an additional shallow undulation that stems from transitions including the more remote $E_1$ and $E_2$ bands. The additional structure exhibits the typical $1/B$-dependence that identifies it as due to transitions originating from the same bands and obeying the same selection rules while involving different Landau quantum numbers. A publication including more data of the same type and a comprehensive analysis of the respective transitions is currently in preparation [17].

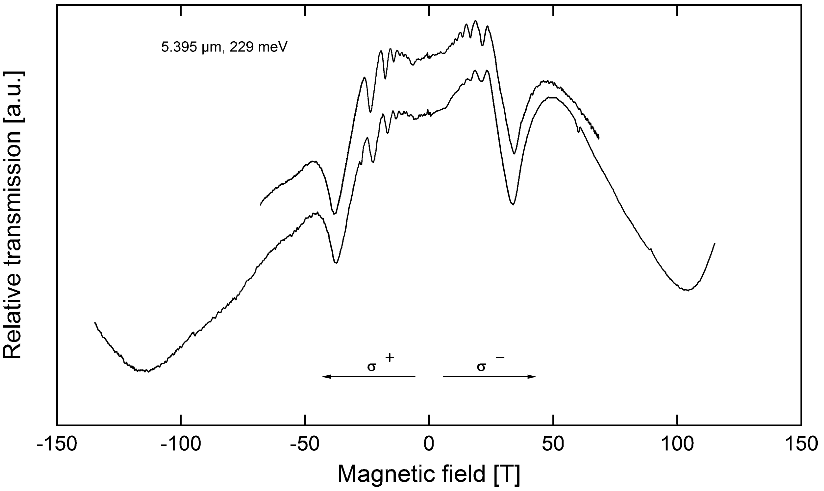

**Fig. 4.** Polarization resolved infrared transmission of graphite up to 140 T indicating the presence of an $e$–$h$ asymmetry as $n \to n+1$ transitions on the left-hand side of the figure are shifted with respect to the corresponding $n+1 \to n$ transitions on the right-hand side. Different coil sizes (10, 12 and 15 mm) and charging voltages (30 and 40 kV) were used in order to optimize both peak fields and the resolution of data at lower fields. The measurements were performed at room temperature with a CO-laser.

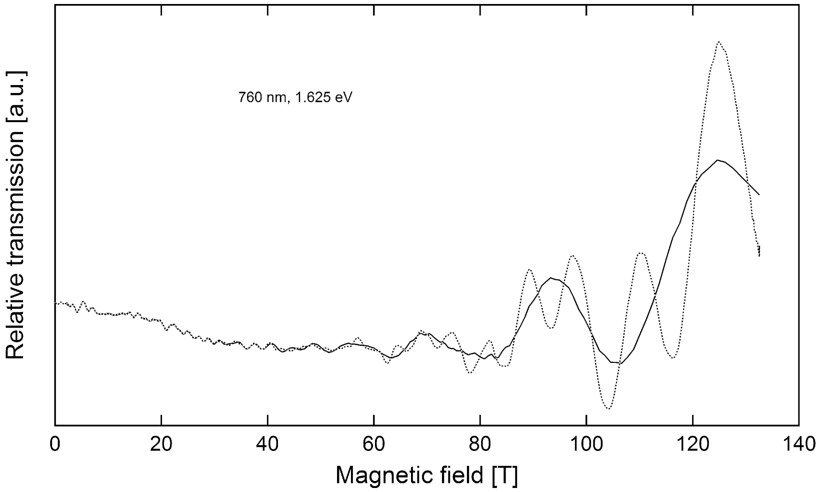

**Fig. 5.** Transmission of graphite at 760 nm. The dotted line shows data as recorded. As compared to Fig. 4 the higher radiation energy now also permits transitions extending beyond the $E_{3+}$ and $E_{3-}$ bands. The additional transitions give rise to a second quantum-oscillatory like feature represented by the solid curve. The latter has been obtained by numerically removing the dominant transitions form the original data. The measurement was performed at room temperature using a simple laser diode.

## 5. Summary and outlook

Magnetic fields well in excess of 100 T can only be generated destructively. Despite their intrinsically short duration and spectacular side-effects Megagauss fields can be a useful tool in solid state spectroscopy and materials research. This is particularly true for single-turn coils whose destruction generally doesn't affect samples and cryostats up to fields of about 250 T.

At the time of writing single-turn coils dedicated to scientific applications exist in three laboratories worldwide, namely the ISSP Tokyo, the NHMFL Los Alamos and the LNCMI Toulouse. All three laboratories are open to external users and are actively promoting new experimental techniques in order to extend the possibilities for solid state spectroscopy in Megagauss fields. The NHMFL Los Alamos is thus undertaking strong efforts to develop wireless techniques for transport measurements. Both the ISSP Tokyo and the LNCMI Toulouse are working on new tools for spectrally resolved optical measurements. As far as peak fields are concerned all three laboratories have the capacity to provide fields in excess of 200 T. The ISSP Tokyo also has an electromagnetic flux compressor providing up to 700 T, albeit at the expense of the total destruction of samples as well as part of the equipment.

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