

Proposal for a 30-T Pulsed Magnet Suitable for Neutron Scattering Experiments

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We describe a conceptual design for a 30-T vertical-field split-pair magnet suitable for neutron scattering studies. While the magnet is primarily intended for diffraction and spectroscopic studies using a pulsed neutron source, it might also have application for relaxational studies at steady-state sources. The magnet will have a 5-cm bore for sample environment equipment, a 1-cm gap for the neutrons to illuminate the sample and through which to observe the scattering. It will run with a repetition frequency of 2 Hz, and a pulse length of 3 ms. We discuss scientific and engineering considerations that led to this specification and describe the designs of both magnet and power supply.

1. Scientific Background

In this paper, we describe a conceptual design for a 30-T pulsed magnet that could be used in conjunction with neutron-scattering apparatus, along with the scientific opportunities that such a magnet might open up. *Neutron diffraction* has long been the technique of choice for determining the arrangements (magnetic structures) of magnetic moments in solids, the spatial extent of the magnetic electrons around their parent ions (form factors) and the full moment-density distribution function in real space. The proposed 30-T magnet would enable one to study such spatial aspects of many field-induced phase transitions for the first time, whether they are driven by competing exchange interactions, single-ion anisotropy, or a more radical change, say from an itinerant to a localised state. *Inelastic Neutron Scattering*, on the other hand, is the best general-purpose tool for the study of magnetic excitations like spin waves, crystal-field levels and spin fluctuations. These excitations manifest themselves in the imaginary part of the generalised magnetic susceptibility $\chi''(\mathbf{Q},\omega)$, which is measured directly in a neutron scattering experiment. A field of 30T acting on a moment of $1\mu_B$ corresponds to an energy of 1.7 meV, and we should be able to generate splittings or close gaps of this order. The present generation of spectrometers at spallation neutron sources have both sufficient resolution (as good as 10 μeV) and sufficient dynamic range (up to 2 eV) to cover the effects that might be induced by such a field.

To first order, one would imagine that almost all zero-field neutron scattering experiments on magnetic systems should be repeated in applied magnetic fields. Likewise, any measurement of bulk phenomena which show interesting properties in fields up to 30 T is likely to benefit from a complementary neutron study in the same field range. Some specific examples of fields of interest for such a combined high-field/neutron scattering capability are:

(a) Field-induced transitions in heavy-fermion materials. Metamagnetic transitions, in which small-moment antiferromagnetism is transformed into a state with moments of the order of $1\mu_B$, have been observed in a number of heavy-fermion

metals: at 8T for CeRu₂Si₂, 24T for UPt₃ and 38T in URu₂Si₂. In URu₂Si₂, 2 intermediate structures¹ both with magnetic unit cells larger than the chemical unit cell have been proposed to explain the magnetisation data. Neutron diffraction experiments would be able to test this hypothesis. In UPt₃, there is a single broadened transition above which "localised" moments appear and one might expect destruction of the heavy-fermion state. However, de Haas-van Alphen measurements² indicate that the masses remain very large even above 24T. It would be of interest both to study the magnetic order in the high-field state and to use inelastic neutron scattering to study the spin-fluctuation spectrum. Perhaps the best idea of what might be achieved comes from the study of Rossat-Mignod et al.³ on CeRu₂Si₂, which has a transition in a field range that is accessible with a d.c. superconducting magnet. The observed magnetic scattering was separated into an "on-site" contribution and "inter-site" correlations. The latter were suppressed above the 8T transition.

(b) Non-Fermi Liquid scaling. One exciting topic at present is that in which paramagnetic correlated-electron systems exhibit power-law or logarithmic dependences in thermodynamic and transport properties. Such non-Fermi liquid behaviour is observed both in f-electron systems and in layered cuprates. One can think of this as the quantum critical behaviour close to a zero-temperature phase transition. Some zero-field neutron experiments⁴ have already been done, but the free energy is expected⁵ to have a particular dependence on H and T. It would be of great interest to map out the excitation spectrum as a function of field, in the same way as has been done for temperature.

(c) Anisotropy in f-electron systems: Both rare-earth and actinide based intermetallic compounds exhibit huge magnetic anisotropies. In the case of rare-earth compounds containing Fe or Co, this anisotropy is exploited to make practical permanent magnet materials. Crystal-field effects are thought to drive the anisotropy. In contrast, the f-electrons in uranium compounds are hybridised strongly with ligand d- and p-electrons, and the magnetic anisotropy results from anisotropic exchange induced by the hybridisation. For antiferromagnets of either case, multiple field-induced transitions have been observed, at fields beyond 20T. Neutron diffraction experiments are needed to understand the structural changes at these transitions, while inelastic scattering experiments in field are likely to reveal the exact role of crystal-fields (via their Zeeman splittings), spin waves (which should exhibit anisotropy gaps) and spin fluctuations.

(d) Gap spectroscopy. Gaps in magnetic excitation spectra can occur for many physical reasons: due to magnetic anisotropy, due to fundamental topological considerations in quantum 1-D Heisenberg materials⁶, due to transitions from insulating to metallic behaviour⁷, and so on. In most cases, it is thought that an applied magnetic field will close such gaps. Very little work has been done along these lines so far.

2. Experience Elsewhere

To date, experience using high fields and pulsed neutron sources⁸ has been concentrated at the Japanese pulsed spallation neutron source KENS⁹, and the Russian pulsed reactor at Dubna¹⁰. In the western literature, considerably more information is available on the two Japanese magnets, which are capacitatively driven water-cooled copper Bitter magnets. One magnet is an 18-T single solenoid suitable for scattering experiments with $2\theta < 10^\circ$. The other is a 16-T split-pair magnet suitable for scattering at $2\theta = 30^\circ$. Its characteristics are listed in Table I. In both cases, the magnet repetition frequency is 0.5 Hz, with a semi-sinusoidal pulse length of 1ms. This results in a strong Fourier component at a frequency of 1kHz, and at this frequency the skin depth of pure copper is ~3 mm.

3. Our Conceptual Design for a Multi-Pancake Coil

In trying to go beyond the Japanese experience, we chose the maximum magnetic field of 30T, and it soon became clear that we need a geometry that allows the current density to spread over a radius greater than the skin depth. We came up with a winding design that uses a small conductor to minimise the eddy-current heating to an acceptable value. Figure 1 shows a simple pancake design whose physical parameters are listed in Table I. It is a radially water-cooled split-pair magnet, whose primary use would be with the field vertical (perpendicular to the neutron scattering plane) as shown in Fig. 2(a). It could also be laid on its side to do experiments with the field in the horizontal scattering plane, but parallel to the incident neutron wave-vector \mathbf{k}_i as shown in Fig. 2(b) or with the field in the horizontal scattering plane but perpendicular to \mathbf{k}_i as shown in Fig. 2(c). The coils would be wound from a single $4 \times 15 \text{ mm}^2$ or double $2 \times 15 \text{ mm}^2$ rectangular Glidcop conductor. The conductor is cooled at its edges with room-temperature water flowing between the individual pancakes. The winding is supported by a 10-cm wide stainless-steel laminate. The magnet would be constructed as two solenoids, with an interchangeable spacer in between. Some structural support would be needed in the gap, but we believe this could be reduced so that 80% of the available angular range could still be used (as shown in Figure 1(a)). In order to increase the neutron count rate, we would flare the support structure out as shown in Figure 1(b).

Capacitatively driven pulsed magnets are essentially resonant LC circuits, and develop a field that is semi-sinusoidal in shape, as shown in Figure 3 (b), with pulse length $\Delta T_{\text{magnet}} = \pi\sqrt{LC}$. Typical neutron pulse lengths at spallation sources are $\Delta T_{\text{neutron}} = 20 - 100 \mu\text{s}$, depending on the moderator and the wavelength of interest. The field should be fairly steady over this time-scale, and therefore ΔT_{magnet} should at least an order of magnitude longer than $\Delta t_{\text{neutron}}$. For our magnet design, we find the minimum heat dissipation for a pulse-length close to 3ms, which meets this criterion.

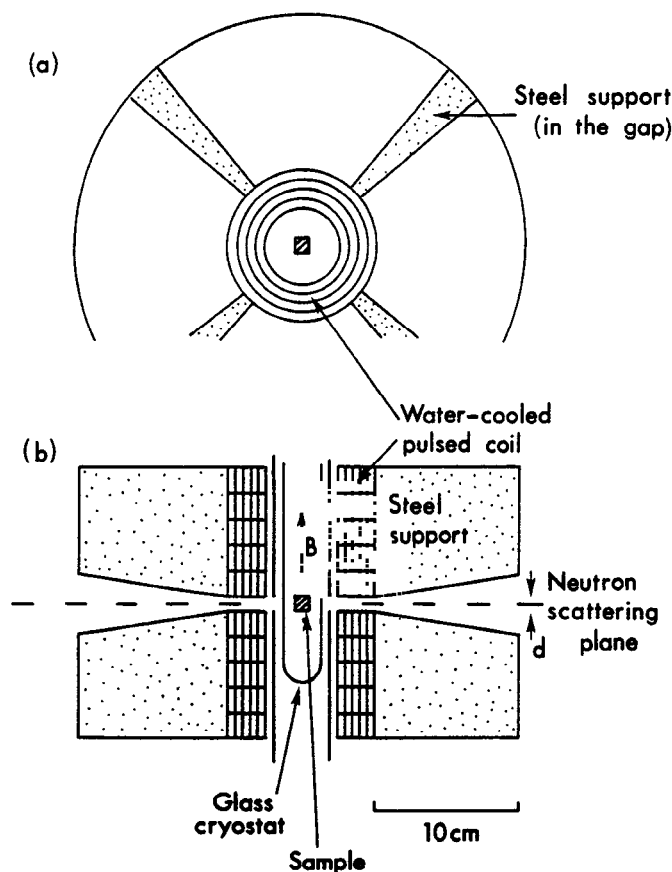


Figure 1. Schematic diagram of the proposed 30T split-pair pulsed magnet for neutron diffraction: (a) plan of an individual "pancake", (b) a vertical section through the whole magnet.

Table I Comparison of characteristics of proposed magnet with those elsewhere

	NHMFL/LANSCE (this work)	Kobe/KENS (Ref. 9)	Dubna (Ref. 10,11)
Maximum field (T)	30	16	15
Field Pulse length, ΔT_{magnet} (ms)	3	1	0.5 - 2
Neutron Pulse length, $\Delta T_{\text{neutron}}$ (ms)	0.025-0.1	0.025-0.1	0.215
Magnet Repetition frequency (Hz)	2	0.5	2.5
Neutron repetition frequency (Hz)	20	20	5 or 25
Gap in split pair (cm)	1(to 5)	1	1
Angular coverage within gap	$4 \times 80^\circ$	$\sim 2^\circ$ at $2\theta = 30^\circ$	
Bore (cm)	5	4	
Capacitance (mF)	17.7	1.2	
Voltage (kV)	6.2	10	
Current (kA)	98	20	
Capacitor energy (kJ)	314	50	
Average heat dissipation (kW)	202		

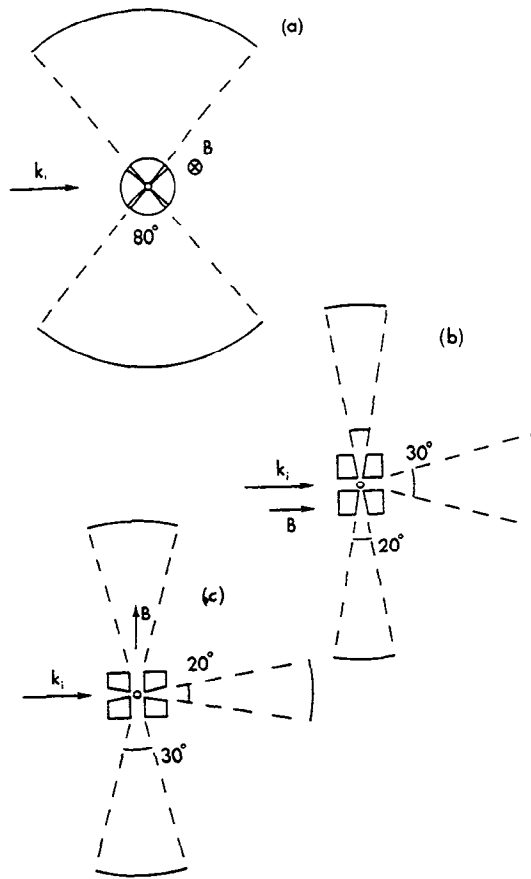


Figure 2. Possible configurations and ranges of angular coverage for the split-pair magnet (a) in the "standard geometry" with \mathbf{B} perpendicular to the neutron scattering plane, (b) with \mathbf{B} in the scattering plane and parallel to \mathbf{k}_i , and (c) with \mathbf{B} in the scattering plane but perpendicular to \mathbf{k}_i .

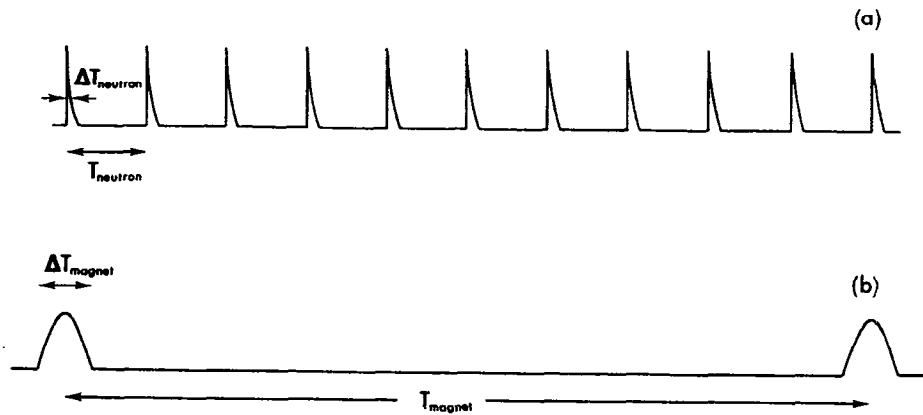


Figure 3. Schematic figure showing the pulse-lengths ΔT and periods T of (a) the pulsed spallation neutron source and (b) the pulsed magnet. In our proposal, $\Delta T_{\text{neutron}} = 25 - 100 \mu\text{s}$, $\Delta T_{\text{magnet}} = 3 \text{ ms}$, $T_{\text{neutron}} = 50 \text{ ms}$, and $T_{\text{magnet}} = 0.5 \text{ s}$.

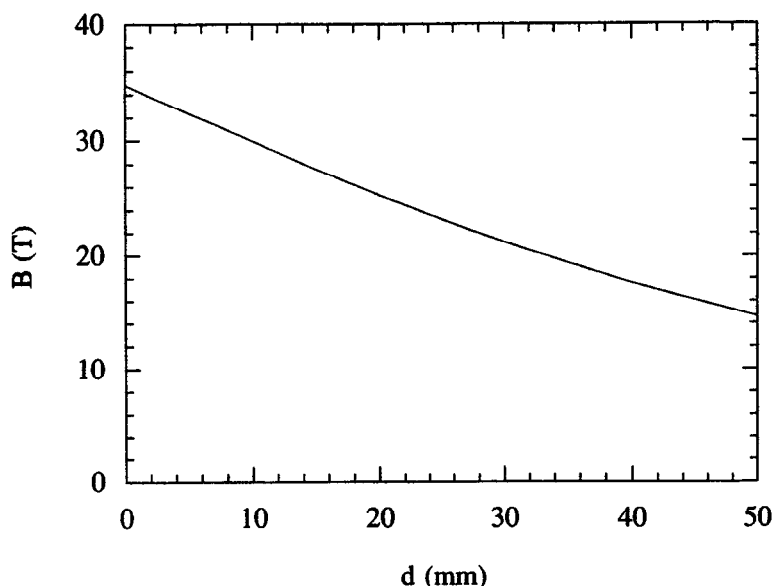


Figure 4. The variation of magnetic field at the sample as a function of gap spacing d .

The next consideration is the repetition frequency of the magnet. Pulsed spallation neutron sources operate at repetition frequencies of 20Hz (LANSCE and KENS) or more (IPNS and ISIS). Neutron scattering experiments are invariably limited by the available neutron flux, so it would be best to use every pulse from the source. However, "normal" pulsed magnets rely on their thermal capacity for cooling: they are bathed in a cryogenic fluid which is boiled off as a result of the field pulse. Cooling such a magnet down again can take several hours. For our application, the magnet must be cooled continuously (by water or liquid nitrogen), in much the same way as d.c. high-field magnets. The saving grace is that the pulse length can be reduced and, to first order, the required power (and cooling) can be reduced by the ratio of the pulse length to the period between pulses. While the KENS/Kobe system operates at 0.5 Hz, we chose a frequency of 2 Hz. In other words, we will use only one neutron pulse out of ten at LANSCE.

The main unresolved technical question with our proposal regards the fatigue lifetime of the components (conductors and insulation) in the magnet. Even in a single day, it will receive more pulses (172,800 @ 2Hz in 24 hours) than most pulsed high-field facilities experience in their whole lifetime. We are about to undertake a mechanical materials-testing program in Tallahassee to examine these issues.

4. Increasing the Gap for Inelastic Studies

For neutron-diffraction experiments (without energy analysis), a sample volume of 1 cm^3 is normally sufficient. However for inelastic scattering experiments, larger sample volumes are required. For instance, on the new chopper spectrometer PHAROS¹² at LANSCE, a beam area of up to $5 \times 7.5 \text{ cm}^2$ can be used. If the gap d is increased to exploit the larger sample height, the penalty in terms of magnetic field is shown in Fig. 4. We also chose the magnet bore of 5 cm in part for similar reasons, so that large samples could be accommodated, and in part so that the full range of cryogenic apparatus might be installed when necessary.

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