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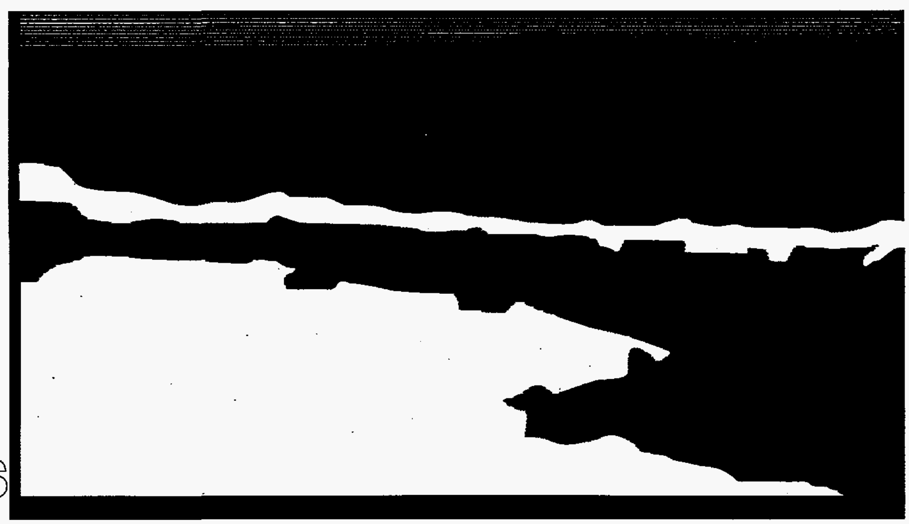

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DIRAC: A Campaign of Experiments to Study Physics and Chemistry at Ultrahigh Magnetic Fields

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Abstract. — We present an overview of the *Dirac* experimental campaign conducted at Los Alamos in spring of 1996. The name was chosen in recognition of P.A.M. Dirac's monumental contributions to quantum theory, which affected every aspect of the science we planned to investigate. We show how the various collaborations were put together, discuss some of the difficulties of collecting data in rapidly changing magnetic fields, describe the motivation, packaging, and integration of experiments, and give an exceedingly preliminary discussion of some of the results.

Background.
This spring, scientists from seven laboratories in four nations gathered at Los Alamos to conduct a campaign of pioneering experiments at ultrahigh magnetic fields. This collaboration among Americans, Russians, Australians, and Japanese is without precedent. Some of the participants were Florida State University, Louisiana State University, Bechtel Nevada, the University of New South Wales, the University of Tokyo, the National Institute of Materials and Chemical Research (Tsukuba, Japan), and the All-Russian Institute of Experimental Physics (Arzamas-16).

The detailed results of the various experiments are either presented elsewhere in these proceedings and or will be published in appropriate discipline-oriented journals. The purpose of this overview is to convey some feeling for how the many experiments were organized, integrated into the magnets, and diagnosed; and to describe some of the difficulties involved.

The Tools and the Challenge.

Figure 1 shows the three magnet designs used in the *Dirac* series. On the left is one of the 50-T class nondestructive magnets at the National High-Magnetic-Field Laboratory in Los Alamos. The magnets consist of exquisitely engineered coils, bound with carbon-filament epoxy, and driven by a capacitor bank. As shown, the magnets are contained in a vault in the event of a destructive failure. These magnets were used mainly for testing apparatus that would be deployed in the explosive-driven magnetic field generators.

The middle picture is a device called a strip generator, which was pioneered by Max Fowler.[1] It uses a single turn coil, constructed by machining-out a block of brass, connected to a triangular flux-compression assembly, which consists of copper channels filled with strips of high explosive. The seed field is created by discharging a capacitor bank along the channels and through the coil. The seed field is then compressed by detonating the high explosive at a the symmetrical point furthest from the coil. The device can reach fields of up to 150 T. Experimental samples are placed in the coil, usually within a glass tube through which cryogenic fluids can be passed. The strip generator has the advantage of an exploding coil, rather than an imploding coil — the experiment is not usually ended by collision with the coil. In principle, experimental sample could be recovered.

The right side of Fig. 1 show one of the Russian-designed-and-fabricated MC-1 generators[2] used in *Dirac*. The seed-field generator of the MC-1 consists of a multitude of epoxy imbedded wires with a circuit comprised of a slightly pitched helix in one direction and wires parallel to the axis in the other direction. Implosion by the high explosive surrounding the seed-field generator cause the many wires to collide and form a single tubular conductor, which compresses the seed field as it implodes. As the flux compression proceeds, the seed-field generator (first cascade) looses its perfectly cylindrical inner surface to rapidly growing instabilities. At about this time it collides with the second cascade consisting of a cylindrical shell of epoxy-imbedded wires parallel to the axis. Until the collision the second cascade has been unable to conduct in the azimuthal direction and has been easily penetrated by the growing magnetic field. When the collision occurs, the second cascade begins conducting in all directions and captures the magnetic field with a clean new surface. The process is repeated by the third cascade, and the ultimate field can exceed 1000T.

Above the MC-1 generator is a plastic helium cryostat designed by Dwight Rickel. The tail of the cryostat is inserted into the MC-1. In lieu of a radiation shield, liquid nitrogen is made to flow down the sides of the cryostat tail. The cryostat can be pumped to below the λ point.

The graphs on the lower portion of Fig. 1 (courtesy of Jim Brooks) illustrate the principal of conducting such high-field experiments: the field of the 50-T class magnet reaches a maximum rate of rise of $\sim 10^4$ $\mathrm{T \cdot s^{-1}}$, the strip generator $\sim 10^7$ $\mathrm{T \cdot s^{-1}}$, and the MC-1 a whopping $\sim 10^9$ $\mathrm{T \cdot s^{-1}}$! Signals must be recorded in the presence of induced electric fields proportional to the rates and heating processes approximately proportional to the squares of these rates. Recovering a clean signal from an unaltered sample is a truly daunting technological challenge.

Some of the Experiments.

Figure 2 lists the principal experiments of *Dirac* and an attempt to illustrate the kind of collaborations that were involved. The chart is certainly oversimplified and does not show the complexities, which may even transcend the formalisms of graph theory.

The *Dirac* series included three ~150-Tesla experiments using strip generators (designated strip-1, strip-2, etc) and three ~1000-Tesla experiments using MC-1 generators (designated MC-1A, MC1-B, and MC-1C). Data analysis for several of the experiments is not yet complete. Here is a rough sketch of the experiments and how they stand at present.

Quantum Limit Phenomena in 2D Organic Metals. Two-dimensional metals may be several orders of magnitude more conducting in the x and y directions than the z direction. Their anisoptropic conductivity suggests that these metals should behave somewhat like a composite of 2D electron gases. At extremely high fields, the magnetic and Fermi energies are comparable, and we enter the realm called the quantum limit, where the behavior of two-dimensional metals is simply unknown.[3] Data was acquired on MC-1A, MC-1B, and MC-1C with a direct transport measurement utilizing micro-PC board coplanar transmission lines with spacings of $\sim 100\mu$m and oriented so that there was practically no open-loop area projected in the direction of $\vec{B}$. The effects of $\vec{B}$ were further reduced by measuring the potential between inner and outer strips causing the noise signals to cancel. Because there were three distinct resonances with quasi-exponential decay, whose origin is unclear, the data will have to be carefully analyzed using a synthetic filter. As described elsewhere in these proceedings, a great deal was learned about direct transport measurements in explosive systems, but it is not clear that any useful data was acquired concerning quantum-limit phenomena in two dimensional metals.

Quantum-Limit Phenomena in Bismuth Semimetal. The experiments lead by the UNSW group all used a pioneering technique for transport measurements in explosively-driven magnetic fields. The microwave band from 1 to 2 GHz is fast compared to the time scale of the MC-1, but $h\nu \ll kT$ for temperatures in the 1K range. By transmitting microwaves on a micro-PC-board coplanar transmission line (in fact, the same kind of board as used in the direct transport measurements described above), filters could be used to reject noise from the high rate-of-change of the field. Results from the transport measurements on bismuth suggested a semimetal to insulator transition near 150T with onset of a precursor at 100T. It was further indicated that a re-entrant state occurred in the range about 250 to 300T. These tantalizing but very tentative result are discussed in more detail elsewhere in this volume.

Quantum-Limit Phenomena in 3D Electron Gas. The prime motivation for this experiment was the possibility of observing magnetic-field-induced superconductivity.[4] Superconductivity derives from a net attractive interaction between electrons in the neighborhood of the Fermi surface. In conventional superconductors the interaction is the sum of a repulsion due to Coulomb force and an attraction due to ionic overscreening. Known superconductors have a critical magnetic field at which all superconductivity is quenched. The critical fields are a function of temperature. But theoretical work has suggested that in the quantum limit (lowest Landau level), the temperature for transition to the superconducting state can actually increase with field. The electron-electron repulsion is screened by the Debye length and it can be shown that, for high enough field, the Debye length actually increases with field. So the electron-electron repulsion can be reduced until attraction dominates.

The parabolic quantum wells were constructed from gradations in $Al_xGa_{1-x}As/GaAs$, the parabolic potential providing a relatively uniform rectangular prism of low-density mobile carriers. The samples became more resistive as the field increased up to about 450T, but gave no evidence for magnetic-field-induced superconductivity. The uncertainties about where such an effect should occur are quite large, but this experiment appears to have eliminated a substantial regime.

Zeeman-Driven Bond Breaking in Transition Metals. The transition metals molybdenum and rhenium have the unusual property of forming quadruple bonds with themselves. Their ground state has 4 bonds, but their lowest excited state has an antibonding orbital and therefore has only 3 bonds. This excited state consists of a singlet and triplet. The singlet is readily accessible by photoexcitation, hence its energy level is known. Little is known about the triplet, which is expected to be much lower in energy. The *Dirac* experiment included an attempt to use Zeeman effect to reduce the energy level of one component of the triplet until it fell below the ground state, effectively breaking the 4th bond, and providing a measurement of the energy level of the triplet state, which has been heretofore inaccessible. While the data analysis is preliminary, limits may have been set on the energy of the triplet state in quadruply bonded rhenium, but apparently we lost the signal to noise in the molybdenum experiment.

Faraday Rotation in CdMnTe. $Cd_{1-x}Mn_xTe$ is a member of a group of materials called, "diluted magnetic semiconductors," which contain magnetic ions (Mn^{2+} in this case) that can undergo an spin-exchange interaction with band electrons.[5] This spin-exchange produces an enormous spin splitting of the energy bands and consequently, an giant Faraday effect. At low magnetic fields and room temperature the Verdet coefficient (which is proportional to the magnetization) is directly proportional to the field. At high fields, however, the Verdet coefficient is expected to reach a saturation level and even decrease slightly. At low temperature and high field, steps appear in the Verdet coefficient that are attributed to the coupling of pairs of the magnetic ions, and more complex clusters of $(3, 4, 5, \cdots)$ magnetic ions.

In *Dirac*, we measured the Faraday rotation of very thin samples of $Cd_{1-x}Mn_xTe$ in two previously unexplored regimes. Both samples were at ~4K and the rotation was observed up to 130 T. For one sample, $x = 0.1$ and $\lambda = 830$ nm, and for the other $x = 0.43$ and $\lambda = 633$ nm.

The $x = 0.1$ sample was placed in a tiny faraday rotation sensor called a quadrature — a four-optic-fiber device designed so polarized light brought in from one end will produce a sinusoidal signal $\frac{\pi}{4}$ out of phase with light brought in from the other direction. The data showed some light leakage on one arm of the quadrature, so the signals had displace baselines. However, the inflections on the Faraday rotation showed five definite points of inflection, which Vadim Platonov has tentatively identified as five level crossings. The $x = 0.43$ sample was placed in a single channel faraday rotation sensor and produced well characterized fringes out to 130T. Vadim Platonov has recently shown these data to be well fit by theory. We emphasize that this is a very preliminary result, and much more careful analysis will be required before we can be confident that we understand the baseline shift. Extension of the data base for this material to ultrahigh field will lead to more complete understanding effect of magnetic clusters in diluted magnetic semiconductors.

Eu^{3+} and Sm^{3+} as Ultrahigh Magnetic Field Measurement Standards. The purpose of the Eu^{3+} and Sm^{3+} experiments was to study the jumps in Faraday rotation that result from mixing when the Zeeman-split excited states and ground states cross each other in energy.[6] The interest in this effect derives from the fact that the critical fields at which the jumps occur are determined only by atomic constants and are unaffected by the environment in which the atoms are embedded. Thus the atoms can be used to set universal standard for measuring magnetic fields in the 1.5 to 50 MG range. In rare earths, the f-shells of f-ions preserve the traits of the free ion. Some data was obtained for the Eu^{3+} on MC-1C, but has yet to be analyzed. The data on Sm^{3+} was lost.

MC-1 Experimental Layout.

Figure 3 (courtesy of Bob Clark) shows the experimental layout of the MC-1 series. The cryostat tail was inserted about half way into the inner cascade of the MC-1 generator creating two distinct partitions. The solid state experiments, which required ~1 K temperatures, were contained within the cryostat tail, and transmission lines were brought up to a connector board at the cryostat head, with six connectors for the semiconductor and semimetal experiments, and six connectors for the organic metal experiments. The bottom partition was maintained at a nominal 77K by the flow of liquid nitrogen around the cryostat tail, and contained all of the experiments that required fiber-optic coupling. Diagnostics for the magnetic field included inductive probes at the center and between the cascades, as well as quartz Faraday rotators in the bottom partition.

Beyond Dirac.

In the next experimental campaign, tentatively scheduled for May 1997, we expect to fire perhaps as many as six strip generators and four MC-1 generators. The strip generators are quite reliable and economical and 130 T seems enough for many important experiments. We believe the MC-1 generators should be divided into two groups: two in a vertical position with a cryostat extending through the entire length of the 3rd cascade — dedicated to ~1K experiments; and two in the horizontal position for temperatures of ~4K and above and experiments that would benefit from "straight-through" fiber optics. Plans for the campaign are still in the formative stages, and we invite bright ideas for experiments that would benefit from these unique capabilities.

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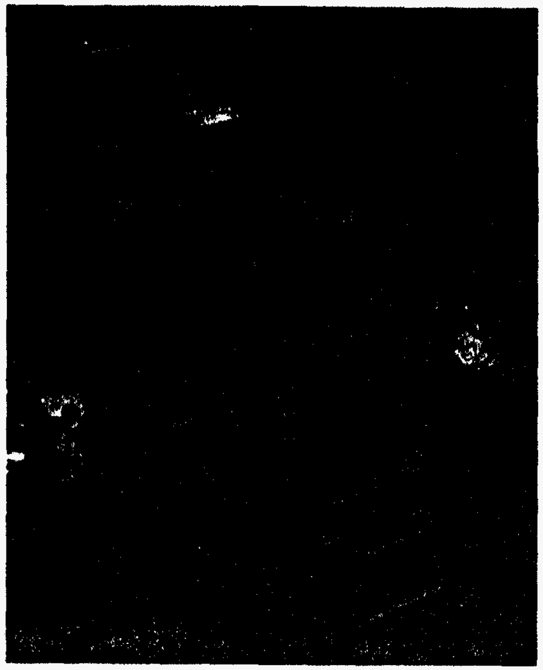
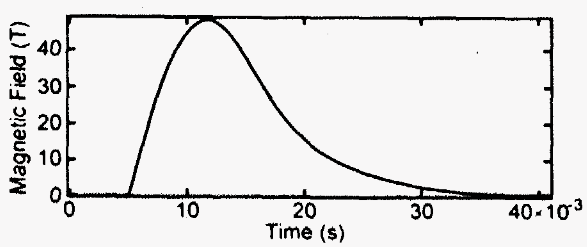
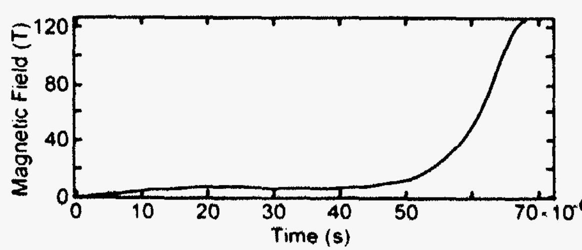
50-T Class Nondestructive Magnet

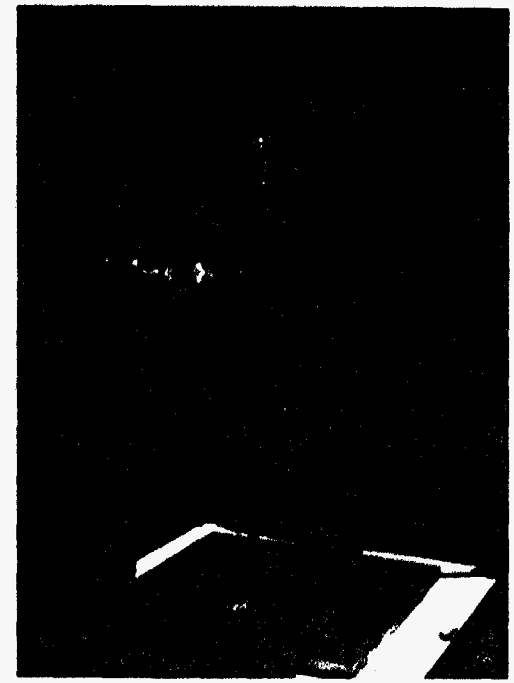


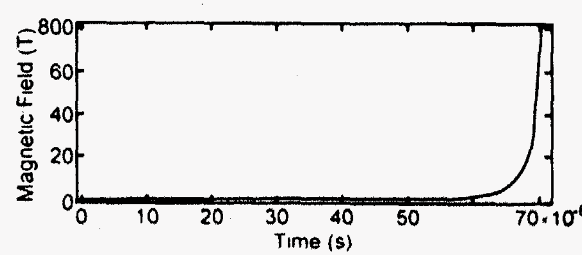


Strip Generator



MC-1 Series





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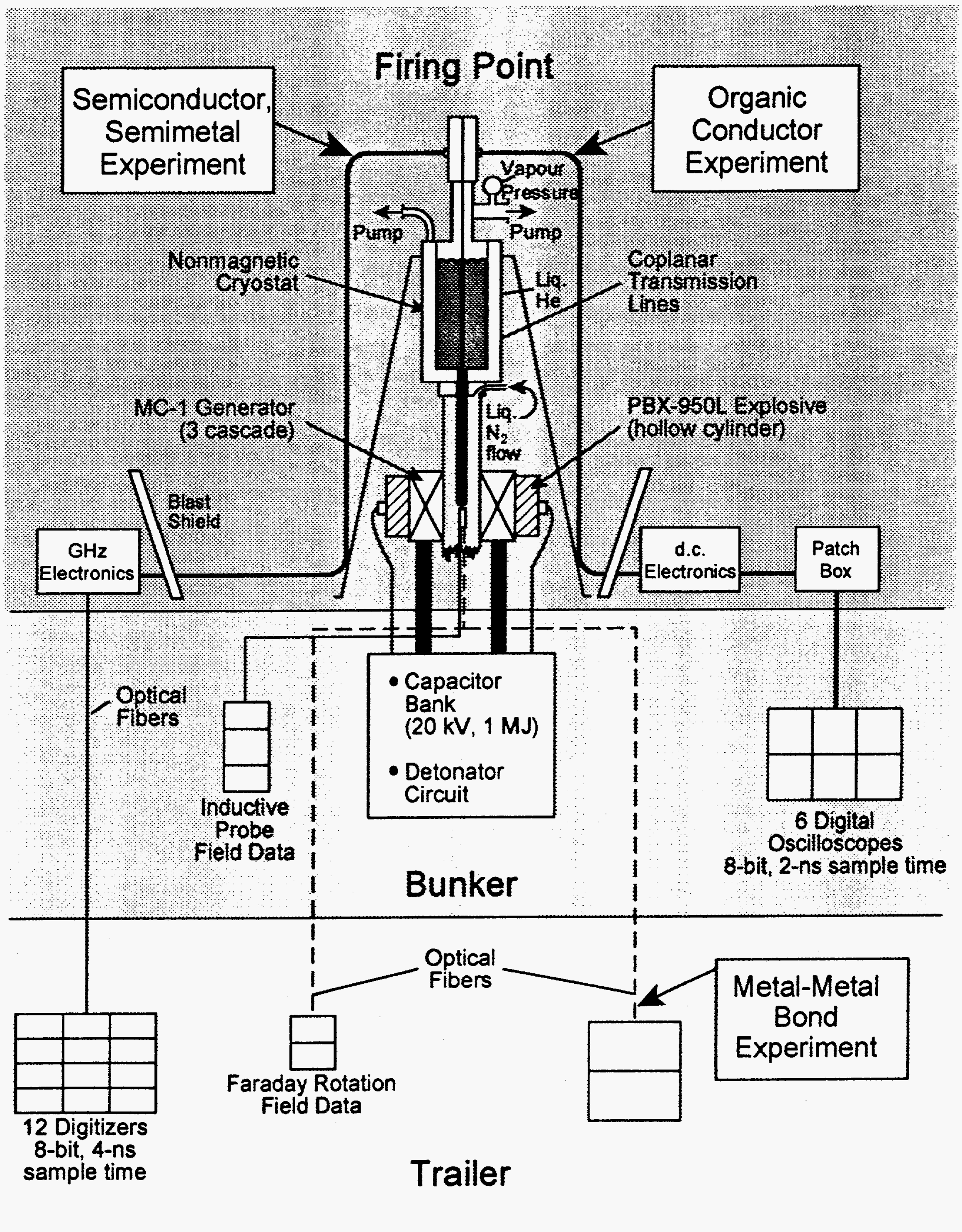
The Dirac high-magnetic-field experimental campaign includes four countries and ten laboratories.

	Quantum Limit Phenomena in 2D Organic Metals	Quantum Limit Phenomena in Bismuth Semimetal	Quantum Limit Phenomena in 3DEG in Parabolic Quantum Wells	Quantum Limit Phenomena in 2DEG in Semiconductor Hetrostructure	Zeeman Driven Bond Breaking $RE_2CL_8^{2-}$ and Mo_2Cl_4	Faraday Rotation in E_u^{3+} and S_m^{3+}	Faraday Rotation in CdMnTe
U of C LANL	Full	Full	Full	Full	Full	Full	Full
Arzamas-16	Partial	Partial	Partial	Partial	Partial	Full	Full
FSU, NHMFL	Full	Partial	Partial	Partial	None	None	None
LSU	None	None	None	None	Full	None	None
UNSW	Partial	Partial	Full	Full	None	None	None
Tskuba, U of T	None	Full	Partial	Partial	None	None	None
Bechtel	None	None	None	None	Full	Full	Full
Lucent Technologies	None	None	Partial	Partial	None	None	None

Collaboration involvement in Dirac series experiments: None = ○ , Partial = ◒ , Full = ●

211b-6/96-ce/jds/jmns

Ancho Canyon



High Energy Density Physics — Los Alamos

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