Pulsed Magnets for Strong and Ultrastrong Fields.

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Abstract—Recent developments in the design of pulsed laboratory magnets are reviewed. There are two general categories with many variations: nondestructive magnets for fields below 100 T with pulse durations from 0.1 ms to 1 second, and destructive magnets with pulse durations from 0.1 to 10 μs. Nondestructive magnets are mostly wire-wound coils with internal and external reinforcement. The peak field depends on the strength of the materials (strong wires, fibre composites) and on the geometry (bore size, distribution of reinforcement and current density) which can be optimized. Megagauss magnets rely on inertial confinement; this is the reason for the short pulse duration. The field is either generated by magnetic flux compression, driven by high explosives or by electromagnetic forces, or in a small single turn coil that explodes violently in the process. The single turn coil is usually driven by a very fast high voltage capacitor bank. Special measuring techniques must be developed for use with the different types of pulsed magnets.

I. Introduction

The laboratory electromagnet is one of the few basic research tools of the experimental physicist. Stronger magnetic fields result in higher resolution and – if luck has it – in the discovery of new effects. Therefore scientists have always made efforts to develop magnets that can generate higher fields [1]. So far, three limitations have been encountered in the pursuit of generating higher fields. First, there was the saturation of iron which sets a limit around 2 T (exceptionally, 5 T). This was overcome by using high power in water-cooled solenoids. The next limit is given by the Joule heating and the power that is of the order of tens of megawatts to obtain fields in the 20-40 T range, requiring very large engineering efforts [2]. This was overcome by using pulsed power which is practically unlimited, and by relying on the heat capacity of the precooled coil which is adiabatically heated during the experiment. The third limit is due to the Lorentz force exceeding the mechanical strength of the coil, leading to coil explosion. Presently, substantial efforts are made to develop mechanically strong conductors and coils with internal and external reinforcement [3]. With a lot of optimism, it is anticipated that fields up to 100 T can be generated without coil destruction. The energy density and the corresponding stress (Maxwell tensor) depend quadratically on the magnetic field, at 100 T (= 1 megagauss) this is 40 kJ/cm^3 or 4 GPa, respectively. For comparison, the energy density of chemical bonding (e.g. fossil fuels) is of the order of 30 kJ/cm^3, and the mechanical strength of the strongest materials presently available is of the order 4 GPa. The mechanical strength of good conductors of electricity (e.g. copper) is of the order 0.1 GPa.

For fields beyond the megagauss limit, techniques have been developed that allow for the destruction of the coil in each experiment. Although this appears to be an extreme technique, it has been demonstrated that it is well suited to do experiments with a reasonable repetition rate. One general feature of experiments with pulsed magnetic fields is the high rate of data output from each field pulse.

II. Nondestructive pulsed magnets

Considering the mechanical strength of available construction materials, it is unlikely that coils can be built to generate fields in excess of 100 T without damage or destruction. Using the most advanced materials and sophisticated coil design, peak fields up to about 75 T have been achieved in half inch bores, and fields up to 60 T are available for daily experimentation. These recent developments in materials science and coil design have given rise to optimism that fields up to 100 T may eventually be achieved nondestructively, and corresponding research projects are under way [3].

One proposed approach is the use of big money, assuming that anything can be achieved if only enough money is invested. In this context, P. Kapitza has been quoted for stating that generating higher fields was mainly a matter of available financial resources. Subsequently, he received substantial funding to build his famous generator and pulsed magnets that he used to perform excellent experiments. However, the peak field of 35 T was smaller than the 50 T he had reported before, and certainly fell short of projected fields in the 50-100 T range.

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It is approximately true that for coils of similar construction, the peak field depends (logarithmically) on the ratio of the outer diameter and the bore [4]. Increasing the outer diameter to one metre or more is expected to yield 100 T at the expense of gigajoules of energy that could be provided from a flywheel. Since the pulse duration is more or less proportional to the energy at the same field level, such a coil could sustain a pulse duration of the order 100 ms or, most optimistically, even one second. Disadvantages of this approach are the high cost, the long development time, the relatively inconvenient operation and - above all - the fact that the big coil ought to be designed ab initio to work with a high degree of reliability. This is difficult to achieve because the high local forces associated with a megagauss field can give rise to unexpected instabilities.

The alternative approach consists in reducing the bore to the tolerable minimum; 8 mm is now considered as the lower limit to accomodate cryogenic equipment as well as for winding stiff wires into a coil. It is anticipated that a compact 100 T magnet can be energized by a capacitor bank with a stored energy of order 10 MJ – still a substantial energy that is equivalent to about 2 kg of dynamite. The pulse duration will be in the range 1-10 ms. It is very likely that the first nondestructive 100 T magnets will have characteristics like these. The real challenge is in the development of experimental techniques that yield good results under these conditions.

III. Multimegagauss destructive magnets

Under the combined action of Joule heating and Maxwell stress, the surface of a metal will explode violently when it is exposed to a megagauss field pulse. This explosion is accompanied by shock waves with associated particle speeds of the order of several millimetres per microsecond. Techniques to generate a megagauss field pulse therefore must be able to concentrate magnetic energy in a time interval of order microsecond. Currently used methods are high speed implosions and very fast capacitor discharges [5].

A. Flux compression techniques

To understand how magnetic flux can be compressed by a rapidly imploding conductor, let us consider a cylinder with radius r, wall thickness d and a length which is large compared to r. The penetration of magnetic flux Φ into or out of the cylinder is governed by a time constant T which is the ratio of inductance L and resistance R:

$$\frac{1}{T} = \frac{R}{L} = \frac{2\rho}{\mu_0 r d} = \left| \frac{1}{\Phi} \frac{d\Phi}{dt} \right| , \tag{1}$$

where ρ is the resistivity and $\mu_0 = 4\pi \cdot 10^{-7}$ Vs/Am. Flux trapped inside the cylinder will decay exponentially with this time constant. If the radius of the cylinder is reduced by implosion in a time interval that is short compared to the time constant, the trapped flux will be compressed and the magnetic field which is the flux density will be increased accordingly. In terms of electrical engineering, the imploding cylinder represents a self-excited electrical generator with the cylinder as the armature.

If the implosion is fast enough to provide for efficient flux trapping, the skin effect comes into play which confines the generated current at the inner surface of the cylinder. The corresponding mathematical model is the diffusion of magnetic flux in a conducting medium. In the "eddy current approximation" where the time scale of magnetic field variation is long compared to the transit time of light in the system, Maxwell's equations reduce to a diffusion equation for the magnetic field B

$$\frac{\partial B}{\partial t} = \frac{1}{\mu_0} \frac{\partial}{\partial x} (\rho \frac{\partial B}{\partial x}) . \tag{2}$$

This can be analytically solved for an exponential field variation $e^{\nu t}$; the solutions are hyperbolic functions involving a skin depth

$$a = \sqrt{\frac{\rho}{\mu_0 \nu}} . \tag{3}$$

When the skin depth a is small compared to the thickness d, this reduces to the simple function $e^{-x/a}$. A useful concept is the flux diffusion speed $v_f = E/B = a\nu$ which governs the diffusion of magnetic flux. It is evident that flux will be compressed as long as v_f exceeds the implosion speed v_i at the inner surface of the cylinder.

In the course of the implosion, v_f increases as the resistivity increases due to Joule heating, and the implosion speed finally decreases as kinetic energy is transformed into magnetic energy and heat. Flux compression comes to an end when the implosion speed equals the diffusion speed; at this point the field goes through its maximum. In the early days of flux compression, this was called the "turnaround" because it was assumed that at this point the imploding cylinder would come to a standstill and reverse its sense of motion. In reality, the imploding cylinder continues to move with the flux diffusion speed and shortly afterwards runs into the probe which is measuring the magnetic field. An example of field pulses with "turnaround" is shown in Fig. 1.

The deceleration of the cylinder due to conversion of kinetic energy into magnetic energy is governed by the compressibility of the imploding material. When the skin depth is smaller than the wall thickness (which is usually the case), the magnetic force is transmitted to the material only within the skin depth. This applies a pressure to the material which results in compression. At a magnetic field of 500 T, for example, the corresponding pressure of 100 GPa will reduce the volume of copper to 74 %. The sound speed in solids is of the order of a few km/s (=

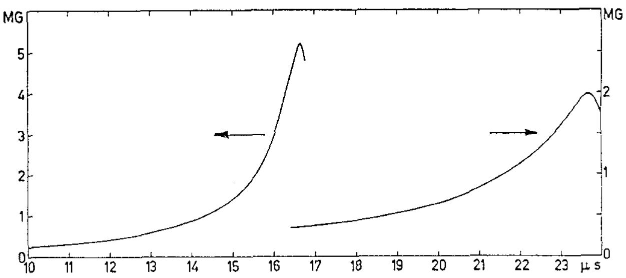

Fig. 1. Magnetic field records from explosive-driven flux compression devices with different liner velocities [6] .

mm/μs) and it increases with pressure. This nonlinearity results in the formation of a shock wave. Once the shock wave is formed, it is governed by relatively simple laws (the Rankine-Hugoniot equations) which represent the conservation of energy and momentum and the equation of state of the solid in terms of pressure, shock speed and the particle speed in the region behind the shock front. For a flux compression, the particle speed is the most relevant parameter as it describes the movement of the surface to which the pressure is applied. From an empirical representation of the equation of state which contains two parameters c_0 and κ, the particle speed as a function of pressure p is given by the equation

$$v_p = \frac{-c_0 + \sqrt{c_0^2 + 4\kappa p/D_0}}{2\kappa} \qquad (4)$$

where D_0 is the normal density. To give an example, for copper c_0 is 3.94 km/s (this is essentially the speed of sound at normal pressure), κ is 1.49 (essentially the compressibility) and D_0 is 8930 kg/m^3. The wall thickness of the cylinder increases during implosion, this results in acceleration of the inner surface. The acceleration implies transport of kinetic energy from the outer layers towards the inside, this is limited by the finite speed of sound and becomes ineffective towards the end of the implosion. The final speed of the inner surface can be estimated from the field increase and from high speed photography [6]. To find the effective speed affecting the flux compression, the (estimated) diffusion speed must be subtracted from this. Experimentally it was found that this simple criterion gives reasonable estimates of the peak field that can be achieved [7], [8].

In the design of a practical device, two essential requirements must be met: introduction of sufficient initial flux and an implosion that is fast as well as regular. To drive the implosion, chemical explosives and electromagnetic propulsion have been used. High precision explosives were first developed at military research centres and were used there to build the first explosive-driven flux compression devices [9]. However, it was later demonstrated that this can also be achieved with the help of private industry [10], [11]. The regular implosion is achieved by initiation with many detonators or by "explosive lens" systems which employ combinations of explosives with different detonation speed. At Frascati, simple "top hat" devices were developed which generate fields of order 500 T with about 1 kg of plastic sheet explosive initiated by one detonator. Such devices could be economically produced for experimental applications. The Pavlovskii group [12] developed implosion systems that generate fields in the 10-20 MG range, these are large and elaborate devices, and thus can be used only for a very limited number of shots. One critical design problem is given by the propulsion system and the coil for generating the initial field getting in each other's way. Moreover, this coil must be not too expensive because it does not survive the experiment. In most devices, a capacitor-driven pulsed magnet is used with a simple coil that is held together by partial inertial confinement until its peak field is reached and then the explosive charge is detonated. One conflicting requirement is that the pulse duration ought to be long enough to allow diffusion of the field into the cylinder, while it must be short enough to assure sufficient inertial confinement. Moreover, the coil and the explosive system both ought to be close to the cylinder and thus are competing for the same space. In the top hat design, this was solved by minimizing the explosive charge and surrounding it tightly by the coil. In the Pavlovskii design, the cylinder (usually called the liner as it is a lining to the explosive charge) is a composite of many parallel thin wires which are insulated from each other. This allows free penetration of the initial flux which is generated by a coil directly surrounding it; when this liner is hit by the detonation wave it becomes a good conductor. Instabilities that develop during the implosion are stabilized by one or more similar cylinders (called "cascades") located at smaller diameters, these are subsequently hit and carried along by the original liner.

The transfer of kinetic energy from the explosive to the liner is limited by the finite speed of the detonation wave, and by the momentum carried away by the detonation products. In practice, it is difficult to obtain liner velocities in excess of 5 km/s. Electromagnetic propulsion is not subjected to this limitation because electromagnetic energy can be transmitted with the speed of light. However, a very large and powerful source of electromagnetic energy is needed to obtain velocities that would generate fields in excess of 500 T [8].

B. The exploding single turn coil

A straightforward method to generate megagauss fields is the fast discharge of a capacitor bank into a small single turn coil [13]. A field B of 100 T corresponds to a current of 0.8 MA per cm axial length (the H-field). The relation between pulse duration and peak field depends on the dimensions of the coil in a nontrivial way. If the coil were sufficiently long compared to its diameter, its expansion would not affect the field/current ratio. However, the energy available from a fast capacitor bank is limited and therefore the coil is axially short, resulting in a decrease of this ratio as the coil explodes violently due to both Joule heating and the magnetically driven shock wave. Fortunately, the sample volume is protected by the magnetic field and even delicate samples and cryogenic assemblies are not destroyed [14]. The single turn coil megagauss generator at ISSP Tokyo [15] has consistently produced a wealth of experimental results since it was set up ten years ago. Recently, at the Humboldt Universität a new experimental facility has been set up that combines d.c. fields up to 20 T from superconducting coils, long duration pulsed fields up to 60 T and a single turn coil for fields in the range from 100 T to 300 T.

The original single turn coil megagauss generator was built at IIT (Chicago) on a shoestring budget, using low inductance coaxial cables and a single solid dielectric switch; the energy was 55 kJ at a peak voltage of 20 kV [14]. The 100 kJ installation at ISSP (The University of Tokyo) was built by the Nichicon company, using a pressurized coaxial spark gap on each capacitor with a peak voltage of 40 kV [15]. The new installation at the Humboldt High Magnetic Field Center [16], [17] has innovative design features. The peak voltage is increased to 60 kV and the energy to 200 kJ; switching is affected by 10 pressurized rail gap switches, each rated at 750 kA. The capacitors are connected via the switches directly to a large parallel plate "strip line" which supplies two experimental stations that can be used in alternation. This design provides for a very low inductance which is the most important factor for obtaining a short pulse duration and efficient energy transfer to the single turn coil. In preliminary tests, severe insulation problems were encountered due to surface discharges onto Mylar sheets when the voltage was increased above 50 kV; this was overcome by using polycarbonate plates as insulating material on the capacitor side of the switches.

For testing new design features, before building the full scale facility a small test rig was built, using two of the units consisting of two capacitors and one rail gap switch each (Fig. 2). A peak field of 200 T was obtained with a coil of 5 mm inner diameter, 5 mm axial length and 2 mm wall thickness (Fig. 3). This small unit will be developed into a compact transportable megagauss generator to be used at the synchrotron radiation source BESSY. The full scale device is now in an advanced stage of construction and is expected to yield ultimate fields in excess of 300 T, and more than 200 T in a 10 mm bore.

IV. Experiments

Experiments must be adapted to the special conditions of the pulsed field environment. This is characterized by small volumes and short pulse duration resulting in spurious induced voltages, eddy current heating and mechanical vibrations. To a degree, this is offset by stronger

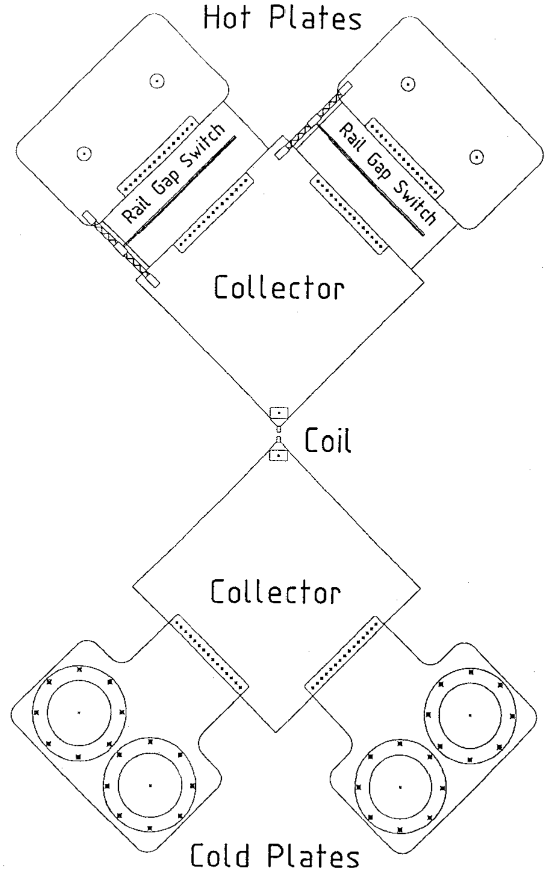

Fig. 2. Drawing to scale of the 40 kJ test facility at the Humboldt High Magnetic Field Center. The drawing is folded open along a line passing through the single turn coil, separating the hot plate and the cold plate of the transmission line.

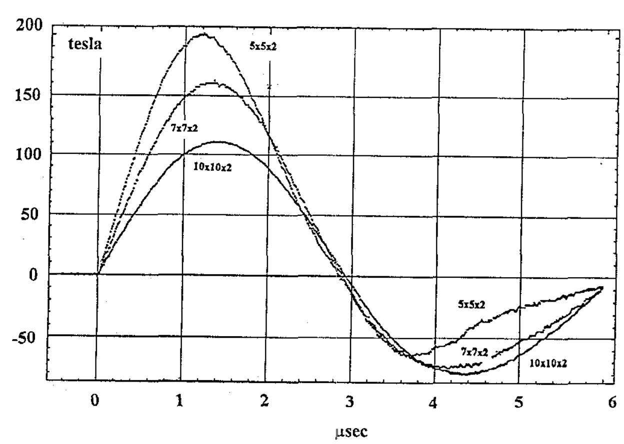

Fig. 3. Magnetic field records from the single turn coil generator shown in Fig. 3. Coil dimensions are given in mm as bore×length×wall thickness.

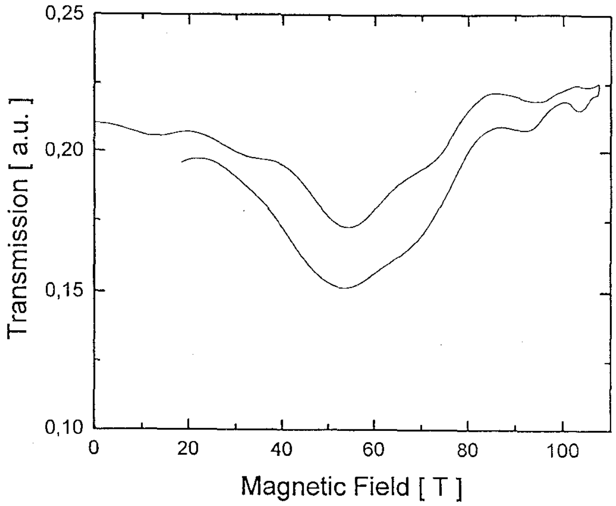

Fig. 4. Magnetotransmission of 114 meV radiation through a quantum well of epitaxial HgSe:Fe at 60 K. The signal is from both the up and down ramps of the field pulse.

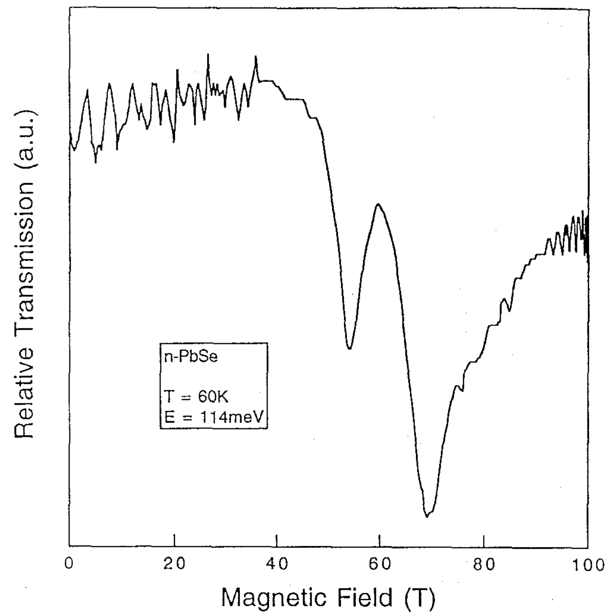

Fig. 5. Magnetotransmission of 114 meV radiation through n-PbSe at 60 K.

signals from the experiments, and by the relaxed requirements on the long term stability of experimental conditions such as temperature. Several laboratories are now installing dilution refrigerators in long pulse magnets, and helium flow cryostats are regularly used in the single turn coil as well as in electromagnetic flux compression. As an example, Figs. 4 and 5 show results from far infrared transmission experiments on a HgSe:Fe quantum well and a n-PbSe sample, obtained at the Humboldt High Magnetic Field Center. The instrumentation at this installation consists of a CO_2 laser, optically pumped lasers and a backward-wave oscillator. In the future, bath cryostats for ^{4}He as well as for ^{3}He will be installed in the vertically oriented single turn coils.

The development of adequate experimental techniques ought to go hand in hand with the development of pulsed magnets. As a guideline, one could propose that approximately equal amounts of funding should be dedicated to both disciplines, in order to get a good return in terms of experimental results from the newly developed pulsed magnets. In particular, extreme miniaturization will not only accomodate experiments in smaller bores, it will at the same time reduce eddy current heating and induced voltages. Digital and optical techniques for signal recording and transmission are developed for high speed recording and for the elimination of electrical noise. At the Humboldt facility, the entire capacitor bank and coil assembly is inclosed in a Faraday cage (Figs. 6 and 7). Signals from the experiment are digitized by a well screened recorder located close to the experiment; the digital information is then transmitted to the outside by an optical fibre link. The 100 MHz data transfer system has already revealed fine structure in the magnetic field record that was not seen previously. The magnetic

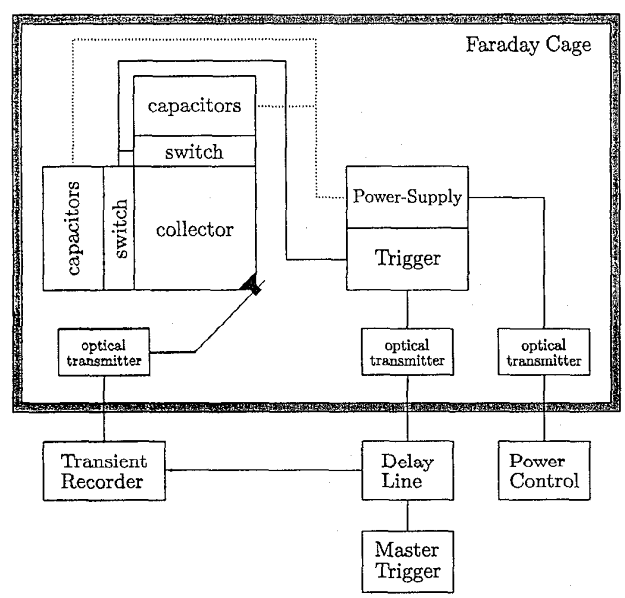

Fig. 6. Schematic of the control and data recording equipment at the Humboldt installation.

field can be measured directly by means of Faraday rotation where all electrical equipment is located outside the Faraday cage.

Finally, it must be recognized that not all types of experiment can be accomodated in the different varieties of pulsed magnets. However, there is a large choice of experiments that can be done, and experimental results of great interest can be expected in the years to come, including the discovery of new effects that advance our fundamental knowledge of nature as well as support new practical applications.

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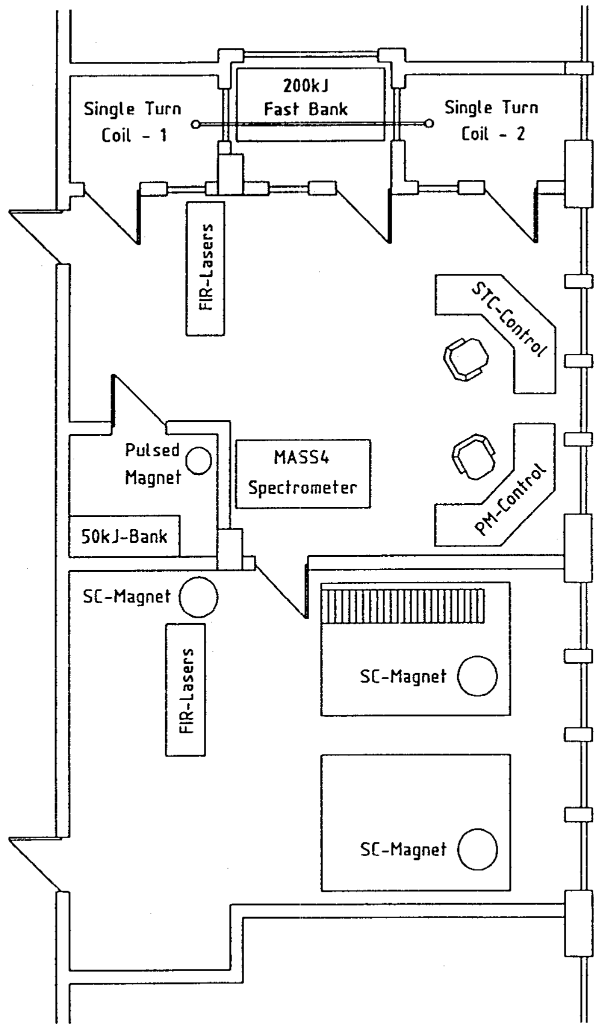

Fig. 7. Floor plan of the Humboldt Magnetic Field Center.