EXPERIMENTS WITH MEGAGAUSS TARGETS AT SLAC*

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Summary

The high pressures and current densities associated with MG fields limit their useful lifetime to 1 μsec or less. The pulse duration of the SLAC electron beam being of the same order of magnitude, a successful marriage of the two techniques was achieved in experiments that use transverse fields in the range 1 to 2 MG as targets for a 19 GeV electron beam. The fields were generated in volumes of dia. 3 to 5 mm by discharging a very fast capacitor bank into small single turn coils, or by flux compression with electromagnetically driven aluminum foils. The termination of the capacitor bank, designed to minimize the destructive effects of the exploding coils, permitted a repetition rate of one shot per hour. Magnetic bremsstrahlung emitted by the electrons was recorded on X-ray film and nuclear emulsions. In an additional experiment, nuclear emulsions mounted in the high field region survived the violent self-destruction of the coils. In these, the magnetic deflection by far exceeds the multiple scattering, which is normally the dominant effect in nuclear emulsions.

Introduction

Techniques for generating megagauss fields have been developed in the past ten years[1]. Since a metallic conductor explodes violently when it comes into contact with a megagauss field, the basic problem is to supply electromagnetic energy at a faster rate than it is dissipated by the destruction of the conductors which confine the magnetic field. A practical solution to this is magnetic flux compression by the rapid implosion of a metallic conductor, usually a cylinder driven by high explosives[2] or electromagnetic forces[3]. The imploding cylinder acts as a mechanical power transformer; it takes up kinetic energy at a slow rate and over a large surface and delivers it to the magnetic field in a short time interval and over a smaller surface. With explosive-driven devices peak fields up to 10 MG have been reproducibly generated. For some applications, a possible disadvantage of the flux compression technique is the waveform of the field pulse which resembles an exponential function with a very fast field rise before the narrow field peak. Megagauss fields of approximately sinusoidal waveform and moderate amplitude can be obtained by discharging a fast high voltage capacitor bank into a small single turn coil[4 5]. The ultra-fast capacitor banks previously used for this purpose were of sophisticated design. For the present work, a capacitor bank has been developed which is relatively compact, easy to operate and quite reliable.

This first experiment with capacitor-generated MG fields is a study of the magnetic bremsstrahlung[6] (synchrotron radiation). Theoretical considerations indicate that experiments of this kind can lead to a direct observation of the radiation reaction and of effects associated with quantum electrodynamics[7]. While the present experiment is not yet in this range, it increases the basic experimental parameters by several orders of magnitude over previous experiments: magnetic field, from 6 kG to 2 MG; electron energy, from 6 GeV to 19 GeV; energy of the bremsstrahlung from ∿ 10 keV to ∿ 10 MeV.

Capacitor Bank Design

Each of the 20 capacitors (14 μF, 35 nH) is connected to the collector by four parallel cables (12' Brand-Rex V-1434). The cable inductance is 16 nH/ft and the ohmic resistance 1.9 mΩ/ft. The peak current per cable is 25 kA, at a bank current of 2 MA. In a number of pre-design tests, cables and connections were subjected to repeated (typically 10) capacitor discharges with peak currents up to 160 kA per cable and a quarter period of 2.5 μsec. The connections and the cables showed no signs of deterioration in these tests. For the connections of the cables to the capacitors the following economical design was adopted (Fig. 1): Two steel bars of cross section 0.5" x 1.5" are bolted together and holes for the cables are drilled through the midplane. The ends of the cables are wrapped in 10 mil copper foil (1 layer) and clamped in these holes. The completed cable termination is mounted on the capacitor as a unit. This design permits a rapid change of the bank capacitance, it is also useful in case of capacitor failure. In one experiment, a capacitor failed when the bank was charged to 15 kV. The termination was not damaged by the discharge of the whole bank into the faulty capacitor. It was quickly disconnected and the experiment continued with a delay of only 10 minutes. The 80 cables are joined on a steel collector as shown in Fig. 2; a detail of the coaxial cable connection is included in Fig. 3. Insulated passages of the same design are provided for the clamping bolts which hold the collector plates together. The insulation of the collector was made by bonding the central insulating sheet (glassfiber-melamine, G-9) and the insulating tubes (glassfiber-epoxy, G-10) to the steel plate by means of Araldite 6010 epoxy[8]. This is the most critical part of the whole assembly because a dielectric breakdown would result in a localized energy release that can cause substantial damage. On the other hand, the insulation has to be kept as thin as possible in order to minimize inductance. When the completed collector assembly was tested at 30 kV, two of the insulating tubes failed. They were easily replaced after drilling out the defective ones. Low

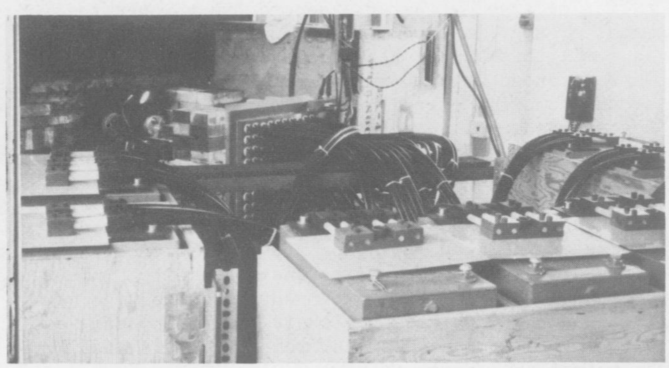
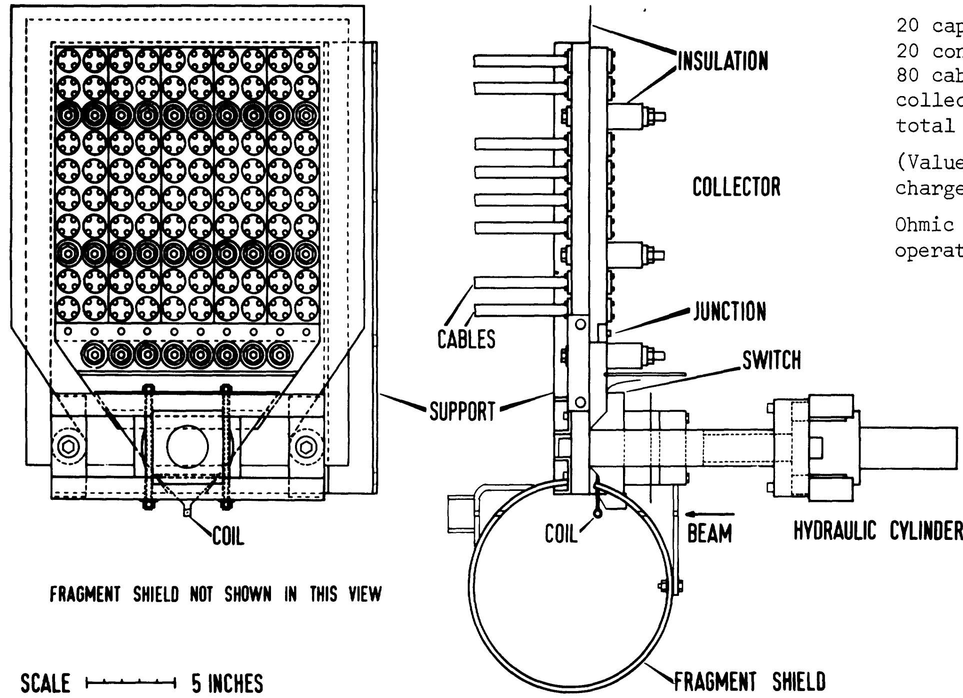


Fig. 1. Rear view of the capacitor bank. In the foreground, the capacitor connections.

* Work supported by the National Science Foundation, U. S. Atomic Energy Commission, and U. S. Army Research Office, Durham.



Distribution of inductance:

20 capacitors	2 nH
20 connections	1 nH
80 cables	2 nH
collector and switch	7 nH (20 nH)
total	12 nH (25 nH)

(Values in brackets are for discharges at 1 kV)

Ohmic resistance, measured under operating conditions: ∿ 6 mΩ

Fig. 2. Top and side view of the collector and the switch.

inductance is achieved by the compact design of collector, switch and terminal in a single unit. The same Mylar sheet is used in the switch and for the insulation of the coil.

The switch is triggered by exploding three bridgewires which are imbedded in the Mylar[9]. The firing unit is a 0.5 μF capacitor, charged to 4 kV and discharged through a Krytron KN6B tube. The inductance of the firing circuit is 2.7 μH. A 1:1 isolation transformer separates the firing unit from the capacitor bank voltage. Alligator clips with pins that perforate the Mylar make contact to aluminum strips which lead the firing pulse to the bridgewires. The bridgewires explode 0.7 μs after the application of the firing pulse; discharge of the main bank follows instantaneously. The total time jitter of the system is less than 50 nsec.

The insulating "packets" are fabricated as follows: Two 1" wide strips cut from aluminum foils (Republic 1 mil "electro-dry" or Reynolds wrap) are joined together with small pieces of acrylic Scotch tape, leaving a 1/16" gap between them. Three aluminum wires of 1 mil diameter are mounted across the gap with small pieces of adhesive tape. These preassemblies are laminated between 1.5 mil Naplam[10] film in a 9 LD laminating machine[10]. After a second run through the machine, the finished packet consists of 4 layers and is 6 mil thick. For high voltage shots, the insulation is reinforced by a 10 mil Mylar sheet which has cutouts at the location of the bridgewires. To improve the contact under all conditions, several layers of aluminum foil are added on each side of the insulating packet in the switching area. For each bridgewire, a pressure relief groove in the shape of 1/3 circle, 0.25" deep, is provided in the top plate. The discharge of the main bank rips the Mylar open along these grooves; this has the effect that the switch inductance decreases with increasing current. Besides the low inductance, which has previously only been achieved with more elaborate designs, this switch is ideal from an operational point of view: Since the coil has to be replaced after each shot, resetting the switch does

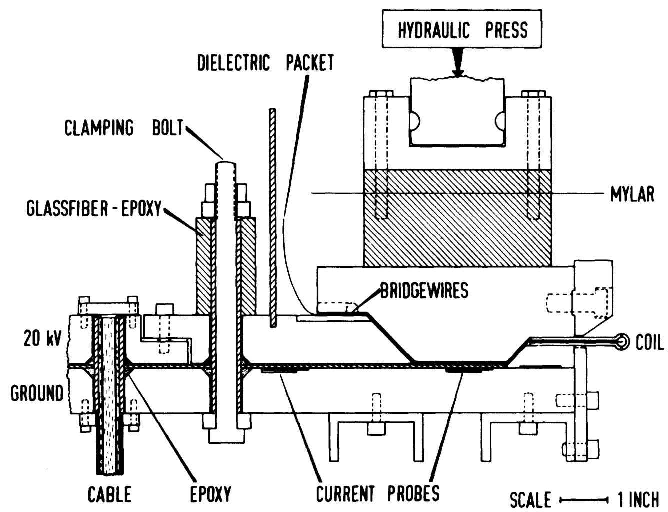


Fig. 3. Cross section of the solid dielectric switch (insulating materials are shaded).

not require any additional work; it is included in the exchange of the coil and its insulation. The hydraulic press reduces the mounting time to a minimum. In fact, most of the time required to prepare a new experiment is used to clean the switch from vapor-deposited metal which originates from the explosion of the coil, and for mounting the magnetic probe. In the present experiment, the total time required to set up a second shot was less than one hour, including beam alignment and placement of the nuclear emulsions. For a standardized experiment, a well-trained crew could operate this switch at a repetition rate of the order of one shot in every 10 minutes.

Single Turn Solenoids

In earlier attempts to generate megagauss fields, very massive coils have been used. Forster and Martin[5] demonstrated that lightweight coils which rely completely on inertial confinement can be made to perform equally well. We have adopted this idea; all our coils were made from metal sheet of 2.1 mm thickness. No difference in performance was observed between coils made of brass or copper. From the point of view of manufacturing the coils, copper was preferred. All coils had beamholes of 2 mm diameter to guarantee undisturbed passage of the electron beam. These beamholes had the effect of reducing the center field by 4%. At the field maximum, the coils are already expanding with a speed of the order of 1 mm/µsec. The exact position of the coils at this instant was determined by means of stereo flash X-ray pictures (Fig. 5) taken with a Fexitron 2722 unit. These confirm that the associated deformation of the beamhole will not cause a disturbance of the beam. Fig. 4 shows a coil before and after the shot. Note the damage caused by the coil fragments. The stainless steel nosepiece was effective in protecting the more delicate parts of the switch from damage. This piece was designed for easy replacement and must be exchanged after a number of shots. The capacitor bank and the surrounding equipment were protected from penetrating fragments by a steel cylinder of 10" diameter and 0.25" wall thickness, placed around the coil as shown in Fig. 2. Some fragments escaped through the beamholes in this cylinder, they were caught in a pipe which enclosed the beam.

Fig. 6 shows the field and current waveforms from a typical shot. The magnetic field was measured with magnetic pickup loops (5 turns, 1 mm diameter) on the axis of the coils, one at the center and one 2 mm off-center. In beam shots the center probe was omitted to avoid interference with the beam. The center field was then inferred from the off-center probe by comparison to calibration shots with both probes. The current was measured with long flat coils of minimized self-inductance which were imbedded in the bottom plate of the switch.

Dimensions and performance of the coils:

Shot	#	C19	C35	C21	C28	C32	C61	C71
ID	mm	10	9.8	5	5.3	5.3	2.2	2.2
Height	mm	10	10	10	10	10	8	8
Bank	kV	10	15	10	12	15	18	20
Peak	MG	.59	.89	.83	.89	1.13	1.48	1.72
At	µsec	3.3	3.0	2.7	2.8	2.6	2.1	2.1
ID*	mm	-	11.1	-	5.8	6.6	4.6	4.7

*at peak field

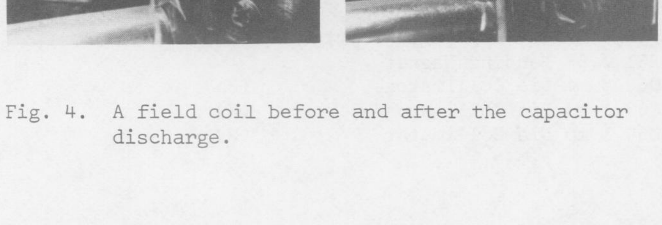
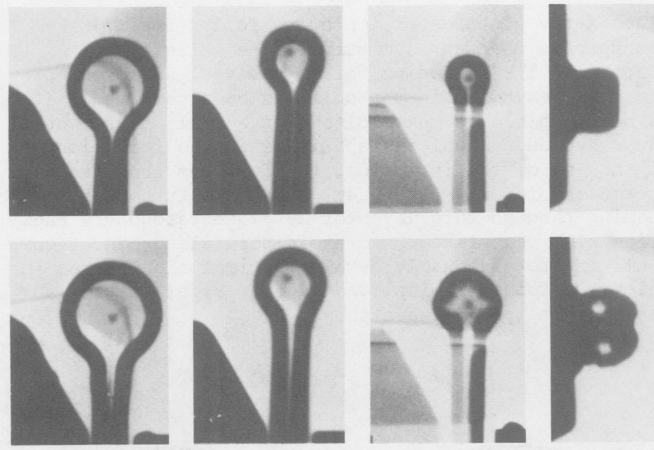


Fig. 4. A field coil before and after the capacitor discharge.



0.89 MG 1.16 MG 1.58 MG side view

Fig. 5. Flash X-ray pictures of coils. Upper row, before shot; lower, at peak field as indicated.

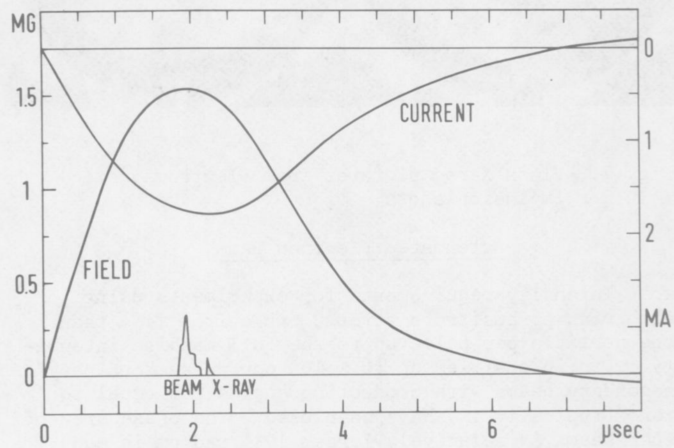


Fig. 6. Field and current record from a coil shot.

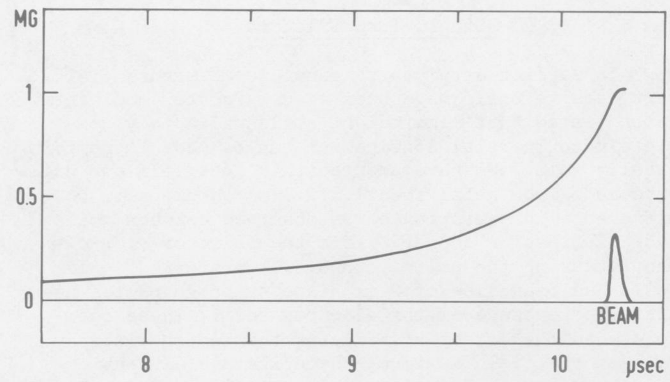
Electromagnetic Implosions

While coils have many essential advantages as megagauss targets, much higher fields can only be obtained with explosively driven flux compression. It is obvious that such extreme techniques are out of the question for a first experimental series such as this one. However, as a general feasibility study for experiments with implosion devices, a small number of electromagnetic implosion shots were included. No satisfactory theory of electromagnetically driven flux compression devices is available as yet. The dimensions of the device were determined on the basis of a previous experimental parameter study[11]:

Coil:	Foil:
inner diameter 1.625"	outer diameter 1.500"
height 1"	height .75"
wall thickness 2.1 mm	wall thickness .018" ± .0015"

The foils were cut from cold-drawn aluminum tubing which has the necessary uniformity of wall thickness. In contrast to previous experiments, the devices were not evacuated. This resulted in a slightly earlier destruction of magnetic probes by the air shock which preceeds the imploding foil. A typical field waveform is shown in Fig. 8. The time synchronization of these devices is much more critical than it is with coils.

Flash X-ray pictures of imploding foils (Fig. 7) demonstrate that an asymmetry of the coils is reflected in the imploding foil. However, no effect of the 2 mm beamholes in the coil has been observed. It is not feasible to make holes in the foil, these would cause hydrodynamical instabilities in the implosion. At the end of the implosion, the foil has grown to a thickness of 6 mm. The beam will be disturbed when passing through this layer of metal and secondary radiation will be emitted. To avoid this disturbance, one could try to eventually develop an implosion system in which two foils are imploded side by side, leaving a narrow slit open between them.



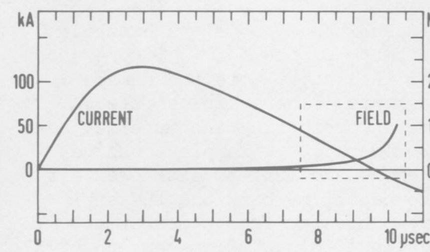


Fig. 8. Field and current record from an electromagnetic implosion shot.

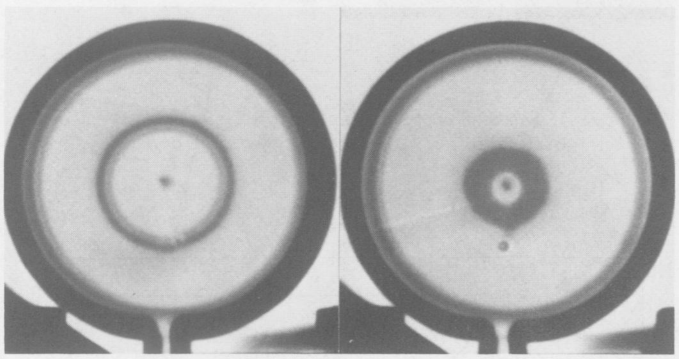


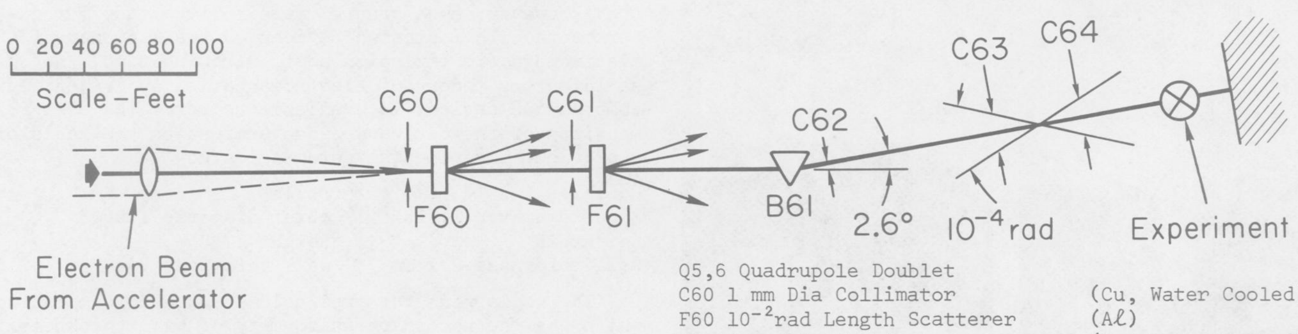
Fig. 7. Flash X-ray pictures from electromagnetic implosion shots.

Attenuated Electron Beam

Intensity requirements for experiments using electrons or positrons at SLAC range from less than one particle per pulse up to the full machine intensity. For intensities up to $\sim 10^3$ per pulse "ordinary" secondary beams with production angles not equal to zero (typically 1°) have been used. The phase area of such beams is relatively large, 10^{-2} rad cm in each plane as compared to 10^{-5} rad cm for the primary accelerator beam. Higher intensities are impractical for such a beam, especially when smaller phase area is needed. At the same time it is impractical to control the accelerator at intensities less than 10^8 particles per pulse.

To provide beams of small phase area with intensities between 10^3 and 10^8 electrons per pulse, a safe technique for attenuating the primary electron beam has been worked out. The attenuating technique consists of first scattering the primary beam with a relatively thin radiator (typically 10^{-2}rad lengths) and then collimating to restore approximately the original phase area in the fraction of the beam accepted by the collimators. Safety is achieved by effecting the overall attenuation with more than one independent stage of scattering and collimation. The critical elements cannot be removed inadvertently; if any one of them suffers beam damage, a vacuum rupture will result. The vacuum rupture would be expected to shut down the accelerator before additional elements of the system could be damaged and thus limit an accidental intensity increase to no more than the attenuation factor in the first of the independent stages.

A schematic of the attenuation system is shown in Fig. 9. The primary beam was focused on collimator C-60 by the quadrupole doublet Q5,6 and was defined spatially with only a small loss of intensity by C-60. The initial scattering occurred in F60, located near C60. The first major attenuation occurred at the collimator C61 and the beam was scattered a second time in F61 located near C61. The second stage from



Q5,6	Quadrupole Doublet	
C60	1 mm Dia Collimator	(Cu, Water Cooled)
F60	10^{-2}rad Length Scatterer	(Aℓ)
C61	2 mm Dia Collimator	(Cu, Water Cooled)
F61	2 x 10^{-2}rad Length Scatterer	(Aℓ)
B61	2.6° Bending Magnet	
C62	6 mm Dia Collimator	(Pb)
C63	1 mm Dia Collimator	(W)
C64	1 mm Dia Collimator	(W)

Fig. 9. Schematic diagram of the attenuated primary electron beam. (Several small steering magnets are not shown.)

C61 to the final defining collimators C63 and C64 provided a still larger, independent attenuation representing the combined effects of scattering in F61 and dispersion in the bend B61. Collimators C63 and C64, together, defined the maximum phase area of the final attenuated and momentum analyzed beam to about 10^{-5} rad cm. With the aid of C62 momentum was defined in the second stage to ± 0.3% at slightly less than primary beam momentum. The thickness of the scatterers F60 and F61 were adjusted so that typical attenuation factors were 1/3 at C60, 1/10 at C61 and 1/3000 at C64 for an overall factor of about 10^{-5}. The beam was operated at 19 GeV with final intensities up to 2×10^7 electrons per pulse.

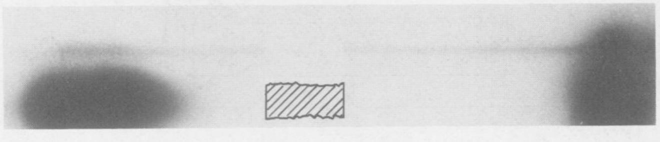
Alignment and Synchronization

To facilitate alignment, the whole switch assembly was mounted on a digitally controlled millbase. For optical alignment, a hinged metal plate could be positioned in the beam line. A small pinhole was drilled in this plate on the beam axis. By illuminating the final collimator from behind and viewing through this hole, the target could be approximately aligned. Final alignment was made with the electron beam itself by inserting a drillrod into the beamholes and positioning the target by remote control for maximum attenuation of the beam by the drillrod. The precision of this alignment was ± 0.1 mm.

Synchronization of a single shot experiment is a problem not usually encountered at an accelerator. This was solved by running the beam at a repetition rate of one pulse per 1 or 2 seconds and using a fast mechanical beam stopper (a magnet-driven tungsten rod). The experiment was manually controlled by two push-buttons: one to open the beamstopper and another to open a gate which transmitted a pretrigger pulse from the accelerator to the capacitor bank control. Usually, one beam pulse was passed to mark the undeflected beam position on the emulsion. This pulse was viewed on the ion chamber and used as a criterion whether to fire the megagauss target on the next pulse. In addition, the two beam pulses were monitored with integrating scintillation detectors. The output of these was also displayed on the set of oscilloscopes which monitored the magnetic field, together with the signal from a beam current monitor. All oscilloscopes were time-correlated by means of crystal-controlled blanking markers. After measuring the time delays of the cabling, the beam pulse could be precisely related to the magnetic field record.

Experiments

The magnetic bremsstrahlung was recorded on nuclear emulsions which are now being analyzed. The time scale of this analysis is measured in years. To indicate whether an experiment was technically successful, X-ray film (Kodak Royal Blue) between intensifying screens (Radelin TF-2) was placed downstream of the nuclear emulsions (Fig. 10). As viewed from the beam, the megagauss target deflected the electrons to the right. A D.C. magnet behind the megagauss target deflected the electrons down in order to spatially separate photons and electrons. The magnetic bremsstrahlung is clearly visible as a narrow horizontal streak. After the first six tune-up shots, all subsequent experiments were successful without exception. This includes four experiments with electromagnetic implosions and peak fields up to 2 MG. As a principal result, this demonstrates that megagauss techniques have now matured to the point where they can readily be applied to experiments.



deflected beam   lead absorber

Fig. 10. X-ray film placed 13 m behind the MG target.

Finally, a simple test was conducted which may open up interesting possibilities for future experiments. Encouraged by the observation that the violent destruction of the coils is directed away from the field volume, and that magnetic probes survived even the highest field shots, we attempted to expose nuclear emulsions in a megagauss field. Professor Heckman furnished a stack of disc-shaped emulsions in a small container that was inserted in a coil of 10 mm i.d. The emulsions were exposed to a single pulse of $\sim 10^3$ electrons in a field of 0.9 MG; they survived the shot without any detectable damage. Preliminary analysis of these emulsions by Professor Heckman indicates that the curvature of the electron tracks can be precisely measured. At "ordinary" magnetic field levels this is not possible because the particle tracks in emulsions are then dominated by multiple scattering. Detailed results from this experiment will be published after the analysis has been completed.

Acknowledgements

This experiment involved the moving of a whole magnet laboratory and yet had to be completed within a half year. This was only possible through the intensive help we received from many people, too numerous all to be mentioned by name, in particular from the SLAC staff. Our experimental site was organized by Finn Hallbo and Glenn Hughes. Dr. G. Svensson contributed to the experiment by calibrating the beam intensity. Professor H. Heckman assisted us with the development and preliminary analysis of the nuclear emulsions. Dr. H. Latal abandoned his theoretical work to help us in assembling the capacitor bank. Philippe Champeil, visiting student from the Ecole Polytechnique, Paris, calibrated magnetic probes and took care of the darkroom work. And finally a very special acknowledgement goes to Ed Petit, our technician, who made many contributions that went far beyond his normal duties.

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