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by W. A. Cilliers, Joseph Norwood, Jr., and G. K. Oertel

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THE PREHEATING OF PLASMA IN A MEGAJOULE THETA-PINCH EXPERIMENT

By W. A. Cilliers,* Joseph Norwood, Jr., and G. K. Oertel
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SUMMARY

The preheating of plasma in a megajoule theta-pinch experiment has been investigated and distinct modes of operation have been delineated. The criteria for satisfactory preionization are discussed. For typical experiments where a number of discharges from different capacitor banks are applied sequentially to a common load, these criteria are determined not only by the requirement for a reproducible and stable plasma, but also by the limitations on the voltage that can be applied to the coil without precipitating prefire of banks that should fire later in the sequence. A range of preheater energies and a bank voltage that are satisfactory for this particular experiment have been determined. Streak photographic evidence of plasma conditions in the various modes is presented.

INTRODUCTION

Theta-pinch devices provide a well-known means for the creation, confinement, and heating of plasmas. (See ref. 1.) The apparatus consists of a capacitor bank which discharges through a massive single-turn coil to create an intense transient magnetic field. The changing flux in the coil creates an azimuthal electric field which drives a current in a preionized gas contained in a quartz tube within the coil. The coil current and the plasma current (of opposite sign by virtue of Lenz's law) repel each other and the plasma is rapidly driven toward the center of the tube, ohmically heated, and further compressed adiabatically. Plasma temperatures of the order of 10^6 °K can be achieved in such an experiment with typical confinement times of 10 microseconds.

Contrary to most experiments which are used to study controlled thermonuclear fusion, the magnetic compression experiment at the Langley Research Center has as its purpose laboratory astrophysics. Conditions are obtained which produce spectra from highly ionized elements introduced as trace contaminants (≈ 0.1 percent) in the hydrogen (or deuterium) working gas. In this way, by controlling the composition of the gas, lines

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may be identified and matched with spectra taken by rocket spectrographs of the solar corona. The chief problem in such an experiment and a very complicated one is that of producing and maintaining the plasma in a stable equilibrium. Only part of the problem is discussed in this paper.

In order to provide repeatable conditions in the main compression discharge, the plasma should be preionized and heated to the order of 10^4 $^{\circ}$K by a low-energy radio frequency discharge. (See ref. 2.) This preionization provides moderately good electrical conductivity for the compression phase of the experiment. The preheated plasma and the trapped magnetic field, if any, must be quiescent in order that the main compression phase would not be turbulent. This paper deals with the problems of plasma preheating for subsequent magnetic compression.

A previous study of these problems has been made at the U.S. Naval Research Laboratory. (See ref. 3.) In reference 3, the emphasis was on precise determination of the temperature and density of preheater plasma. The present paper, however, is concerned with the determination of operating conditions so that the banks can operate sequentially without prefire and so that the plasma produced is quiescent. Spectroscopic investigation of the preheater plasma parameters at the Langley Research Center has been reported in reference 2.

The operational aspects of the preheating problem have not been previously discussed in detail. The problems are common to all such experiments; however, the particular solution to the problems is valid only for a given experiment. Thus, the operating conditions for optimum preheating which are set forth in this paper apply in part only to the experiment at the Langley Research Center; however, the means by which these parameters were obtained should be of general interest.

MAGNETIC COMPRESSION EXPERIMENT

A schematic of the magnetic compression experiment at the Langley Research Center is shown in figure 1. The experiment has a main capacitor bank with maximum stored energy of 1 megajoule. Provision is made for the switching of two other banks to the coil at appropriate times relative to the beginning of the main discharge. These additional banks are the B_z bank, which gives a slowly varying magnetic field of the required amplitude and polarity, and the preheater bank, which gives a high-frequency discharge of short duration to ionize the gas (hydrogen or deuterium at 100 millitorr filling pressure) in the tube prior to the main discharge. Particulars about the three banks are given in table I. In subsequent sections, the effects of the B_z and the preheater discharges on the behavior and the properties of the plasma during the first half-cycle of the main discharge are discussed.

TABLE I.- DESCRIPTION OF BANKS

	Main bank	B_z bank	Preheater bank
Maximum stored energy	1 MJ	50 kJ	7.2 kJ
Discharge period . .	50 μsec	120 μsec (variable)	5.2 μsec $\left\{\begin{array}{l}\text{Full bank,}\\ \text{12 cables}\end{array}\right.$
Maximum voltage . .	20 kV	10 kV	40 kV
Fractions of bank	2/3 and 1/3	Any 1/10	Any 1/6
Usual working conditions	Full bank at 10 kV 1/3 bank at 20 kV	6/10 bank at 8 kV	20 kV $\left\{\begin{array}{l}\text{Usually}\\ \text{4/6 bank}\end{array}\right.$
Maximum field strength	11.5T	4.8×10^{-1} T	3.9×10^{-1} T

The 400 main-bank capacitors are connected in pairs with each pair connected to the 4.8 by 1.2 meter collector plates through two 5.2-meter coaxial cables by means of an open-air spark gap switch. (The performance of these switches was discussed in reference 4.) The collector plates are mass loaded by 40 tons of lead to limit the amplitude of their deflection under the force imposed by the current pulse.

The load coil consists of sections 15.2 cm long with 10 cm bore, bolted directly on the collector plates. There is a gap of about 3 mm between each section to allow optical measurements to be made. The maximum coil length is approximately 140 cm when nine sections are used.

Diagnostic techniques are mainly spectroscopic. A 1-meter Czerny-Turner spectrometer is used to monitor the continuum emission in the visible range. In addition, the intensity of the H_β line is monitored. A vacuum ultraviolet instrument looks end-on at the discharge tube and measures the intensity and wavelength of various spectral lines. Side-on streak pictures of the discharge are taken through one of the slits between coil sections near the middle of the coil. The voltage across the collector plates is monitored through a 90-ohm cable connected in series with a 10-kilohm resistor across the collector plates. Figure 2 shows a general view of the collector plates, coil, and some of the diagnostic equipment.

OPERATIONAL PROCEDURES

The firing sequence of the three banks is as follows: B_z bank, preheater bank, and main bank. The relative timing was essentially as shown in figure 3. Here the subscripts z, ph, and m refer to the B_z, preheater, and main bank discharges, respectively, and $\tau_{z,ph}$ and $\tau_{ph,m}$ are the time delays between firing of the B_z bank and preheater, and the preheater and main bank, respectively. B_m represents the field caused by the main discharge. The amplitudes of the fields in figure 3 are not drawn to scale. The precise time differences between the firings of the banks are determined by various considerations. For example, in order to assist in keeping the plasma formed by the preheater away from the tube wall, the preheater bank is fired while the B_z field is growing. The same 20-kilovolt pulse which is used to trigger the preheater switches is used to form a weak axial discharge in the tube. This discharge provides sufficient preionization to enable the small electric field (70 V/cm) induced by the preheater to cause immediate breakdown. Axial preheating by a Z-pinch is not, in general, satisfactory for this machine since its use precludes the observation of the spectra end on. Spectral work in the vacuum ultraviolet range is most conveniently done end on; therefore, the weak axial pulse has been replaced, since this study was made, by a 50-megahertz, 0.5-kilowatt radio frequency generator which is coupled capacitively into the system. This replacement does not affect the results of this study. The main bank is usually fired at least 25 μsec after the beginning of the preheater discharge by which time the oscillation of the preheater current in the coil has decayed. (See section "Preheating of the Gas.") The behavior of the plasma during the first half cycle of the main discharge depends on, among other things, how much magnetic field is trapped inside and also on the direction of this trapped field relative to that of the driving field. Experiments by many workers have shown that the ultimate temperature of the plasma is higher when the polarity of the trapped field is opposite to that of the driving field. Also, the closed magnetic field lines formed in this case inhibit plasma from escaping from the coil region toward the ends of the discharge tube. (See ref. 5 for a discussion of reversed field trapping.)

The period of the B_z discharge is dictated by the considerations mentioned. For the present investigation a period of 120 μsec was used. In order to have a wider choice in the times of preheater firing, the second half cycle of the B_z discharge was used. This procedure also eliminates any effects that transients in the B_z current may have on the development of the preheater plasma if the preheater is fired simultaneously with or shortly after the B_z discharge. The period and amplitude of the B_z field can be varied by changing the parasitic inductance in the circuit; and the amplitude alone, by changing the voltage.

PREHEATING OF THE GAS

The preheater serves to create sufficient conductivity in the gas so that when the main bank fires, a discharge will form almost immediately at the beginning of the first half cycle. Experience has shown that this condition may be attained even with a preheater plasma of very low energy content. It has been observed at Langley Research Center as elsewhere (ref. 3) that adequate preheating is not attained unless a reversal of the magnetic field occurs during the oscillation. It is possible that some of the electrons are accelerated to relativistic speeds by betratron effect during field reversals (ref. 6) and that these electrons serve as an effective ionization agent. End-on framing pictures have been obtained at the Langley Research Center and at the University of Maryland (ref. 7); these pictures show a spiral structure in the tube suggestive of the trajectories of the electrons in Schmidt's relativistic E-layer theory. (See ref. 6.) Typical examples are shown in figure 4.

Even though a very weak preheater discharge will guarantee a magnetic compression event on the first half cycle of the main bank as long as the preheater pulse produces field reversal, it is preferable to produce a preheater plasma whose state may be more easily determined and reproduced. Ideally, when the main bank is fired there should exist in the tube a highly ionized, pure, and uniform plasma with no trapped magnetic fields other than the predetermined B_z field. In practice, it is difficult to achieve this ideal state. Usually, the more energy one puts into the preheater discharge, the more turbulent the plasma becomes. In order for the plasma to become quiescent, $\tau_{ph,m}$ may have to be so large that at the time the main bank is fired, the degree of ionization may be no higher than it is when a less energetic discharge and a short $\tau_{ph,m}$ are used. Also, when the preheater discharge is very energetic, it will liberate impurities from the wall, and thus contaminate the plasma. It will be shown that above a certain preheater energy, the plasma during the main compression seems to be unstable even if $\tau_{ph,m}$ is made as large as 80 μsec. Here the B_z-field was not applied. It is also essential that the conditions created by the preheater be reproducible.

The preheater is made up of 12 capacitors with one switch for every two capacitors. Any combination of these six pairs could be charged to a maximum voltage of 40 kV.

EXPERIMENTS AND RESULTS

The aim was to find the optimum values of preheater energy. For this purpose the main bank was fired at fixed voltage (20 kV) with preheater voltage and capacitance as variables. The diagnostics used were as follows: (1) side-on streak pictures; (2) H_β intensity; and (3) continuum intensity – two channels used at 4861 ± 200 Å with each channel 40 Å wide. The parameters of the preheater bank that could be varied were

(1) the charging voltage (up to 40 kV); (2) the capacitance (in steps of 1.5 μF up to a maximum of 9 μF); and (3) the parasitic inductance $L_{ph,p}$. The preheater and main bank circuits are represented in figure 5 where

$L_{ph,p}$	preheater parasitic inductance
L_c	coil inductance
$L_{m,p}$	main bank parasitic inductance
$V_{ph,c}$	preheater voltage across coil
C_p	parasitic capacitance of collector plate and load cables

The preheater parameters could not be chosen with complete freedom. The main bank cables to the collector plates are essentially open-ended as seen by the preheater discharge. Voltage doubling at the main switches therefore occurs when the preheater fires. These switches, already stressed by the main bank voltage, may have excess voltage and premature breakdown of some or of all of them may occur. High-frequency parasitic oscillations in the tank circuit formed by the capacitance of the collector plate and cables and the inductance L_c of the load coil will increase the problems.

It is obvious that there is a maximum value of $V_{ph,c}$ that can be tolerated without having premature breakdown. The value of $V_{ph,c}$ is controlled by the voltage on the preheater bank and by $L_{ph,p}$.

A considerable fraction of the parasitic inductance $L_{ph,p}$ is in the cables connecting the preheater bank to the collector plates. The number of these cables could be changed from a maximum of four per capacitor to one per capacitor. This change gives a range in $L_{ph,p}$ of 47 nH to 60 nH. (The inductance of the preheater capacitors with their switches is 43 nH which represents the lowest possible value of $L_{ph,p}$.) Because of the voltage doubling at the main spark gaps explained earlier, it was necessary to limit $V_{ph,c}$ to about 2 kV by a suitable combination of the preheater bank voltage and $L_{ph,p}$. Table II gives, for one cable per capacitor, the values of $L_{ph,p}$ and $V_{ph,c}$.

The effectiveness of the preheater discharge in producing a plasma of the desired degree of ionization was judged from the amplitude of the continuum and H_β signals, from the repeatability of the properties of the preheater discharge alone, and finally from the repeatability of the plasma properties during the first compression of the main bank discharge.

TABLE II.- PROPERTIES OF PREHEATER CIRCUIT

[Inductance of each cable, 204 nH; inductance of each capacitor, 516 nH; coil inductance ≈ 10 nH]

Capacitance, μF	Charging voltage, kV	$L_{ph,p}$, nH	$V_{ph,c}$, kV	Preheater energy, kJ	Mode (*)
4.5	20	120	1.50	0.90	I
3	25	180	1.30	.94	I
6	18	90	1.80	.97	I
9	16	60	2.30	1.15	I
6	20	90	2.00	1.20	I
7.5	18	72	2.25	1.22	II
9	18	60	2.50	1.46	II
7.5	20	72	2.50	1.50	II
9	20	60	2.85	1.80	II
7.5	25	72	3.10	2.34	II
9	25	60	3.50	2.81	II

*Mode I represents low energy; mode II represents high energy.

It was soon evident that the reproducibility of the main bank shots was critically dependent on the preheater energy. There was an abrupt improvement in spectral reproducibility and stability of the main discharge when the preheater energy was below a certain level. There seem to be two distinct modes, referred to as the high-energy and low-energy modes. Figure 6 gives an example of a streak picture of the main compression after preheating in the high-energy mode (here $\tau_{ph,m} = 25$ μsec). The plasma drifts to the wall in 8 to 12 μsec. This drift is due to field curvature caused by the collector plate geometry. This curvature causes charge separation in the plasma and thus gives rise to an electric field which drives the drift. Corrective modifications have been carried out since the present work. Apart from the drift the plasma is clearly unstable. It was found that in this mode plasma stability is not improved if $\tau_{ph,m}$ is increased even up to 80 μsec. For the discharge in figure 5 the preheater energy was 1.46 kJ.

When 0.9 kJ was used at 20 kV (a reduction by a factor of about 1.6 in energy being thereby given), there was a substantial improvement in the gross stability (except, of course, the drift) of the plasma as can be seen in figures 7(a) and 7(b). The difference to be noted between figures 6 and 7 is that in figure 7 a well-formed column is evident whereas in figure 6 the column never forms and the plasma is chaotic from the beginning of the discharge.

The preheater plasma was then studied without the main bank being fired. The charging voltage was kept fixed at 20 kV and the energy increased in steps by changing the capacitance. The change over from one mode to the other is illustrated by the streak photographs of figure 8. At low energy the time-resolved streak pictures show striations corresponding to each current half cycle. When the energy is increased, the ionization tends to persist from one half cycle to the next and also for a longer total time. When 1.20 kJ is used as in figure 8(c), the light (as recorded by the streak camera) extends almost to the end of the streak. With 1.50 kJ, the striations no longer stand out clearly but the light intensity still falls off with decreasing amplitude of the voltage (as expected). However, after about 20 μsec, there occurs a more or less sudden increase in light intensity. At the end of the streak the plasma appears to be brighter than at the beginning. The change over from one type of streak picture to the other is very repeatable and corresponds to a change in energy from 1.20 kJ to 1.50 kJ and to a change in $V_{ph,c}$ from 2 kV to 2.5 kV as can be seen from table II. The preheater voltage necessary for mode I operation is well below that at which premature breakdown of the main bank switches occurs.

The streak pictures in figures 8(a) to 8(c) and 8(d) to 8(e) represent modes I and II, respectively. In mode II the light intensity first falls off and then increases again after about 20 μsec.

By using various combinations of capacitance and charging voltage, it was established that pictures corresponding to mode II are obtained whenever the energy exceeds 1.20 kJ. Photoelectric signals from the spectrograph monitoring H_β and the neighboring continuum are shown in figure 9. The upper traces are continuum and the lower traces are H_β for each of the streak photographs of figure 8. One notes a rise in the H_β signal after a relative minimum at about 13 μsec for the mode II signals (figs. 9(d) and 9(e)) whereas the mode I signals show a monotonic decay with time except for peaks corresponding to each new half-cycle. The spectral reproducibility was better in mode I than it was in mode II.

The reason for this changeover is not clear but could be caused by impurities. However, the preheater discharge was relatively weak and one would not normally expect to contaminate the plasma with wall impurities. The only explanation seems, therefore, to be that with the higher energy the plasma escapes from the ends of the coil region and hits the tube wall. When this contaminated plasma then comes back along field lines into the coil region, the light output increases as observed on the streak photographs. For this same reason, the main discharge is less stable when mode II preheating is used.

CONCLUDING REMARKS

It has been found that there is a satisfactory low-energy mode of operation of the preheater corresponding to a coil voltage of 2 kV or less and an energy of 1.20 kJ or less from which a repeatable plasma suitable for magnetic compression may be obtained. The voltage limitation is due to the limitation on standoff voltage of the main bank switches. This result is, of course, applicable only to the experiment at the Langley Research Center. The energy limitation is a more general result. For higher energies there is apparently an increase in the contamination of the plasma by wall materials. This condition causes turbulent behavior in the main compression phase.

The problem of creating a breakdown at such low voltages and adequately preionizing with such limited energy has been solved by using a weak discharge just before the preheater is turned on and by arranging the timing of the preheater relative to the B_z bank discharge so that field reversal will occur.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 20, 1968,
129-02-01-02-23.

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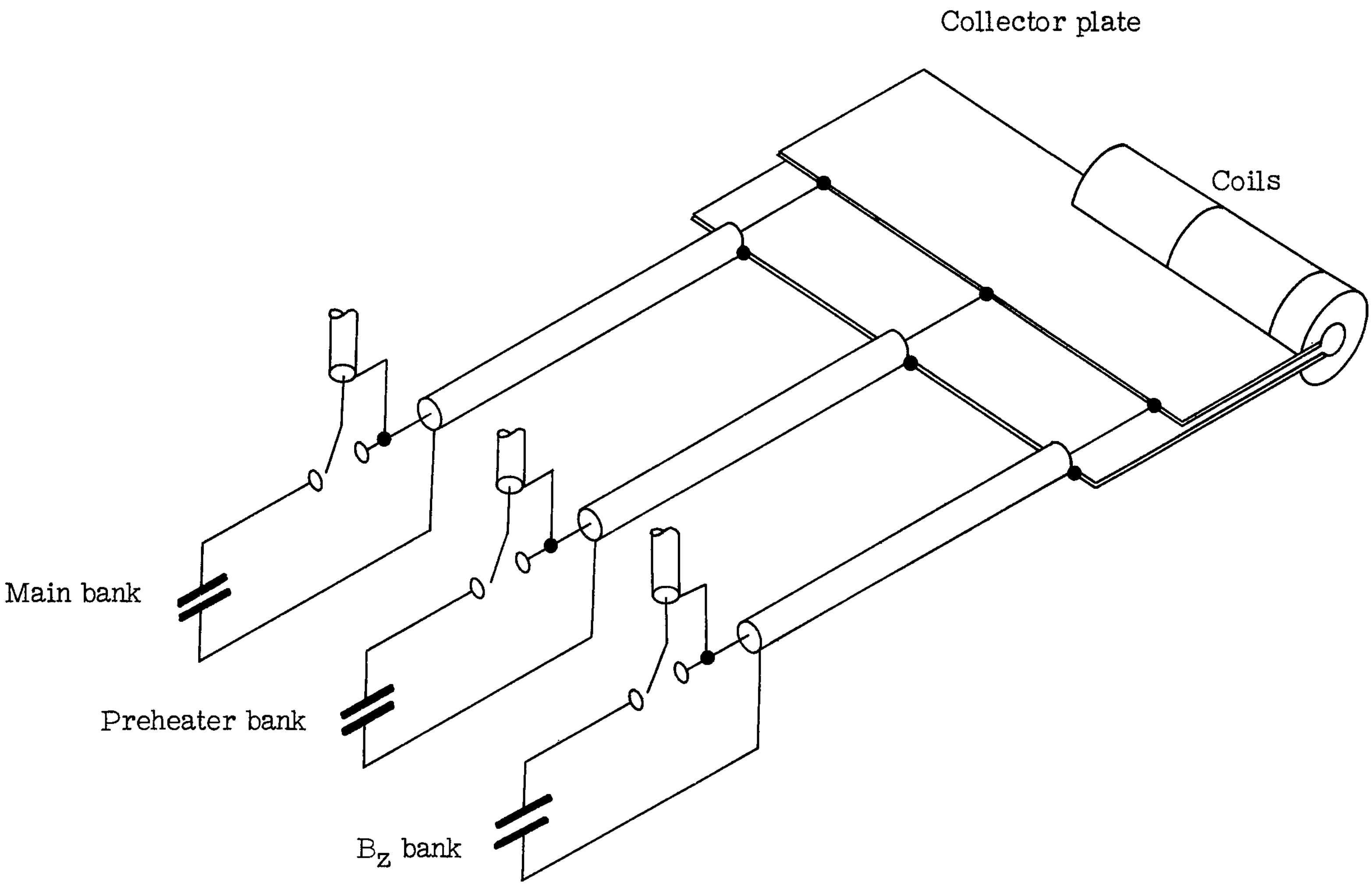

Figure 1.- Schematic of capacitor bank and collector plate system.

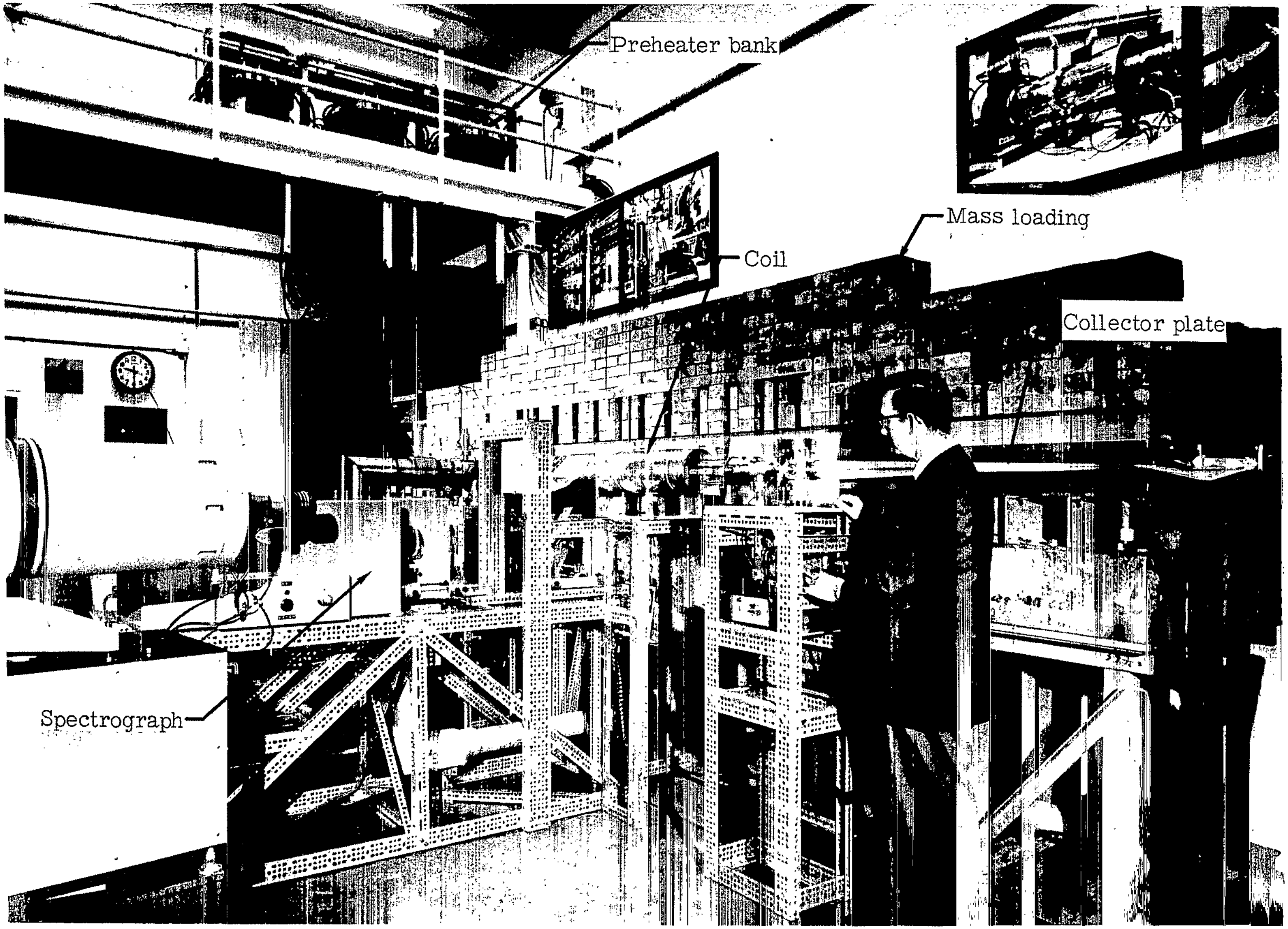

Figure 2.- General view of the experiment.

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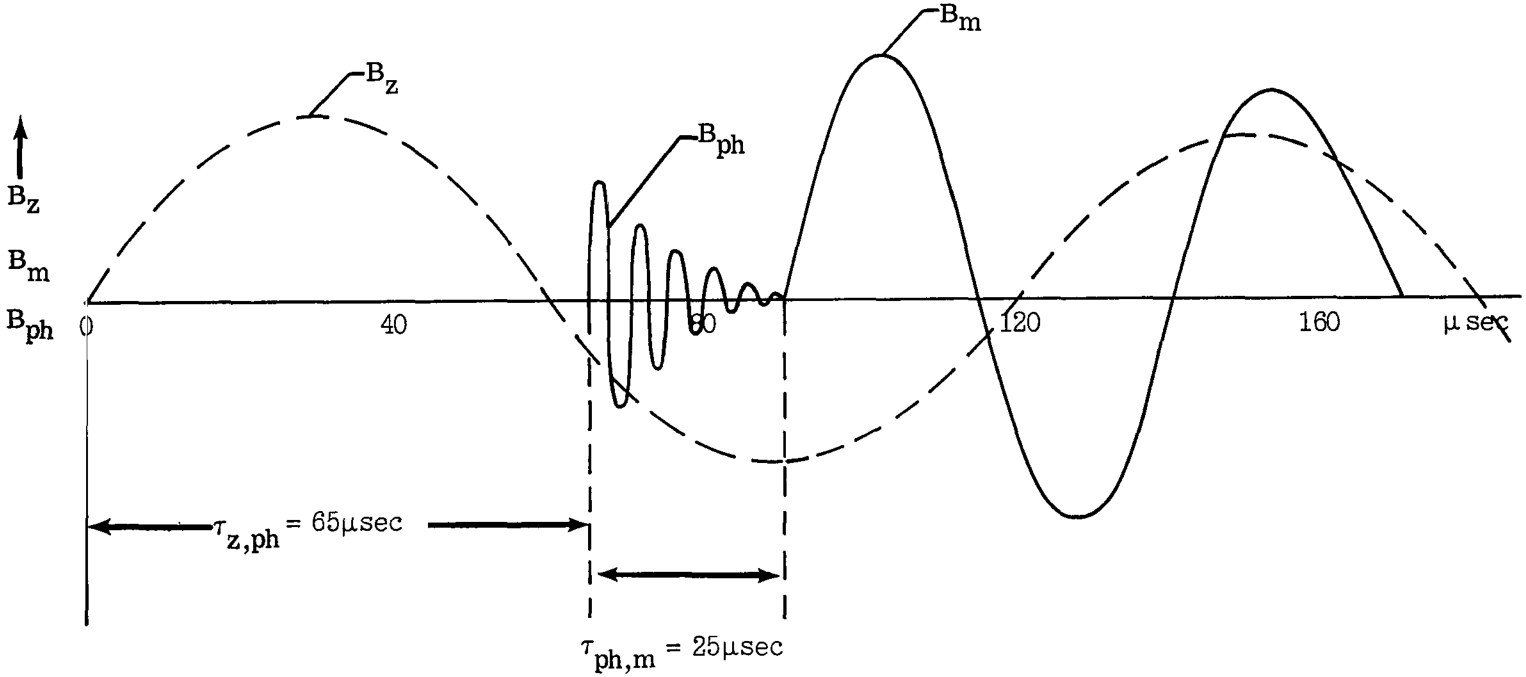

Figure 3.- Timing sequence of the banks.

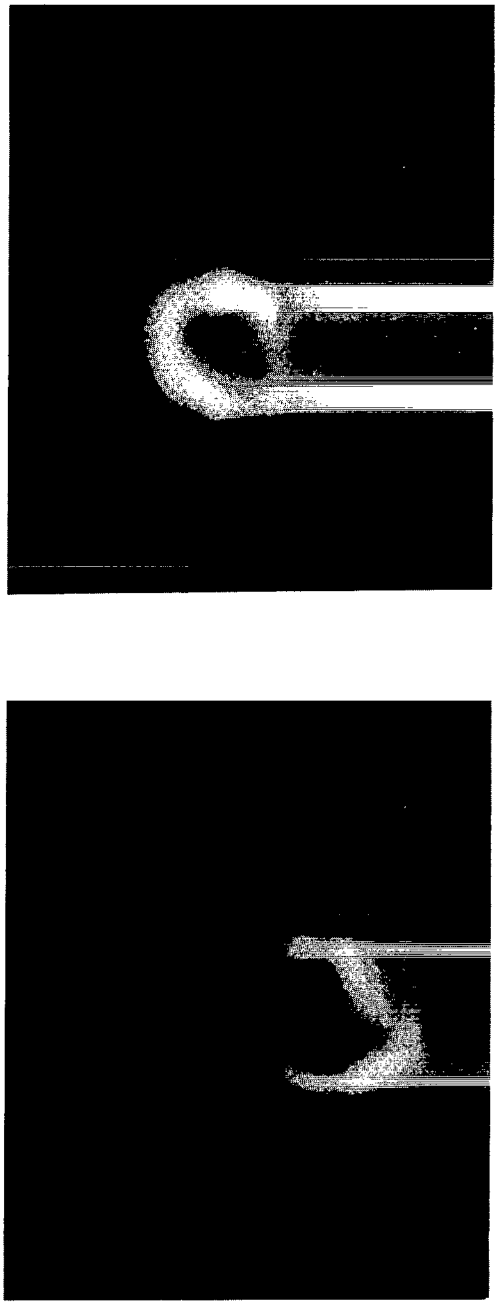

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Figure 4.- Examples of spiral structure. Photographs taken end on with image converter camera.

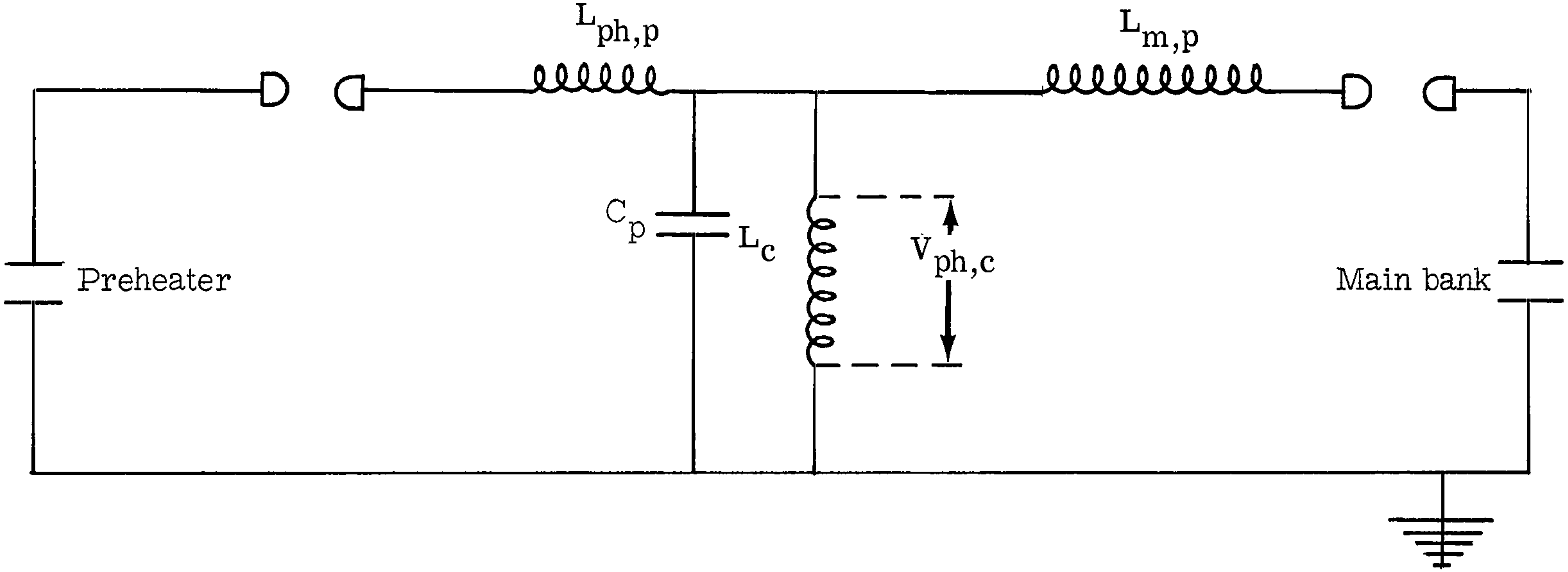
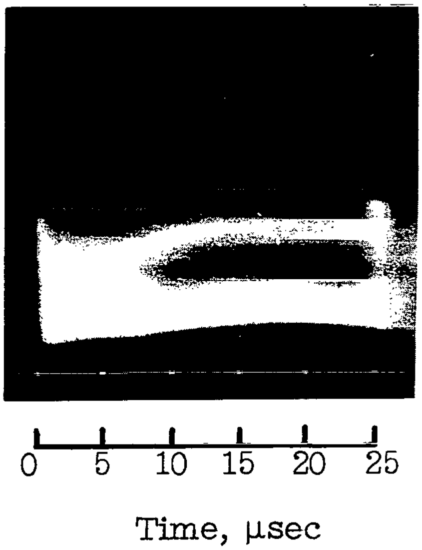
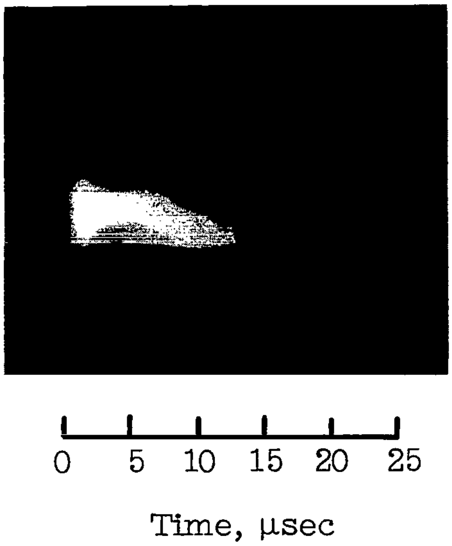


Figure 5.- Schematic of the discharge circuit.

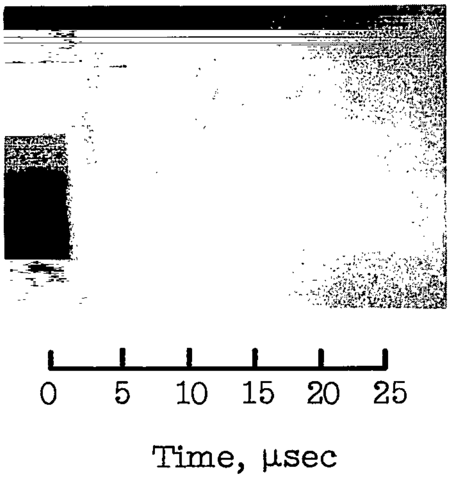


L-68-864

Figure 6.- Streak picture showing the high-energy (turbulent) mode. $\tau_{ph,m} = 25$ μsec. The sinusoidal shape of this and the following figure is due to perturbation on the electron optics of the image converter due to the magnetic field.



(a) $\tau_{ph,m}$ = 25 μsec.

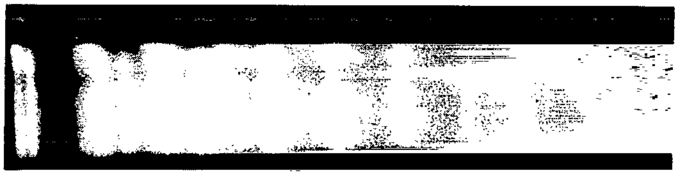


(b) $\tau_{ph,m}$ = 25 μsec. L-68-866

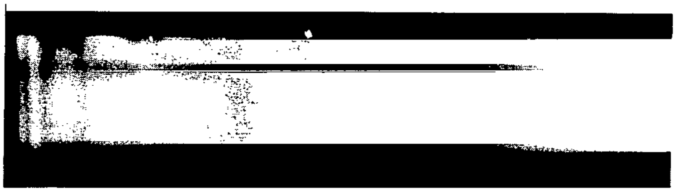
Figure 7.- Streak pictures showing the low-energy mode.

(a) 0.60 kJ

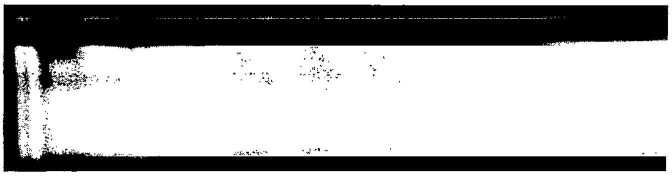
(b) 0.90 kJ



(c) 1.20 kJ



(d) 1.50 kJ



(e) 1.80 kJ

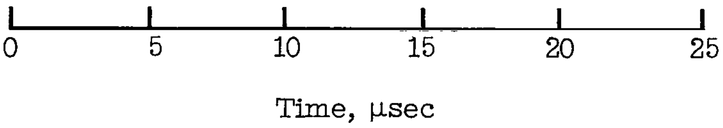
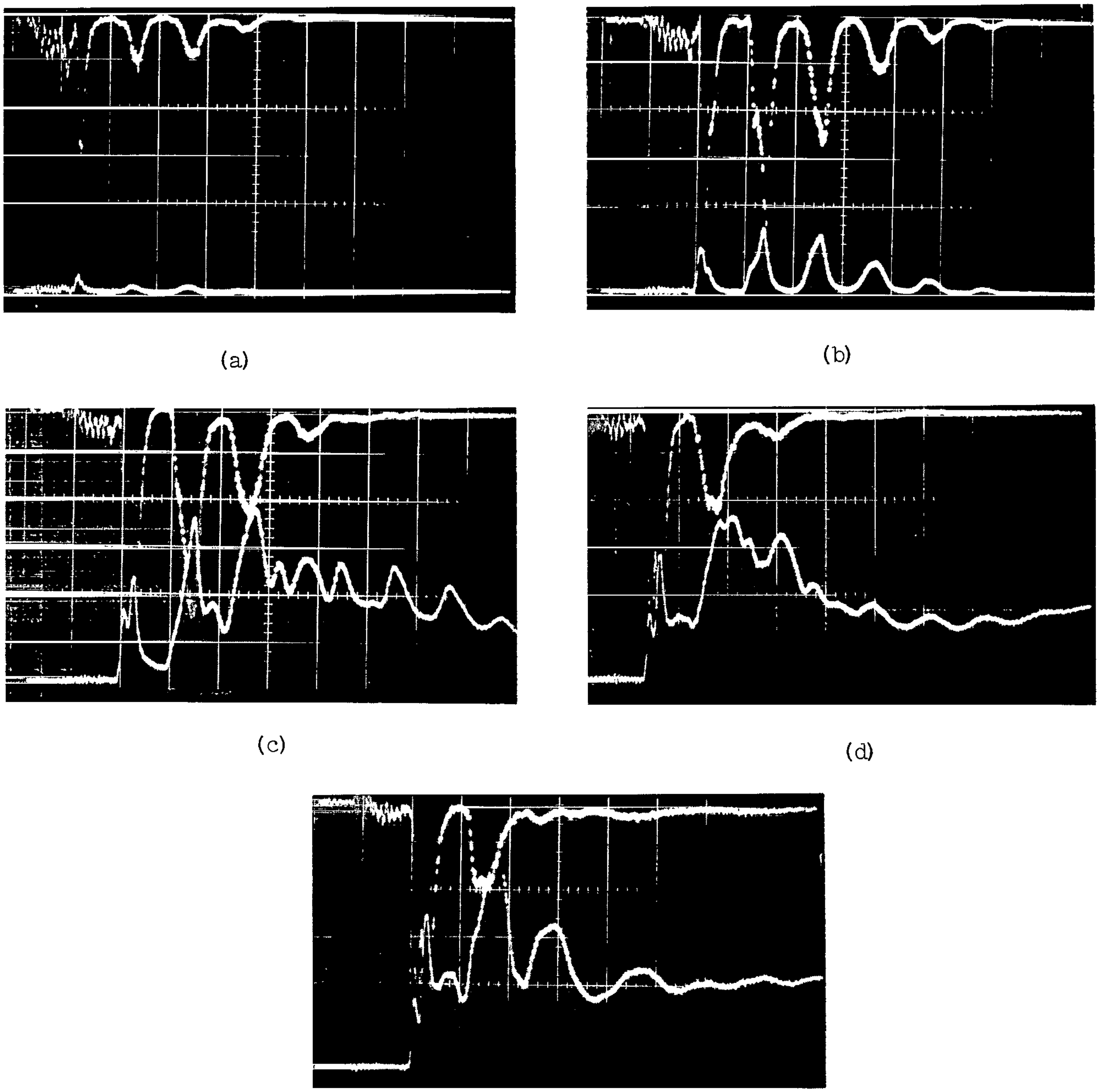


Figure 8.- Streak pictures of the preheater discharge. L-68-865



(a)

(b)

(c)

(d)

(e)

Figure 9.- Continuum and Hβ line intensity corresponding to the streak photographs in figure 8. Upper trace, continuum; lower trace, Hβ; sweep speed, 2 μsec/cm.

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