SLAC-PUB-1247
(I)
May 1973

A REPORT ON FAST CYCLING BUBBLE CHAMBERS AT SLAC†

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The linear accelerator at SLAC, because of its high pulse rate, is perhaps the accelerator most suited to the use of fast cycling chambers. As a result of this good match we have stressed the development of rather speedy chambers.

The 82-inch chamber, which pulses steadily at two times a second, has performed well for 5 years and has a total of about 50 million pulses and 18 million pictures.

The 40-inch chamber is somewhat faster and runs routinely at 10 pulses per second. This chamber has taken 85 million pulses and 4.6 million pictures. Its best use lies in hybrid experiments in which a reasonably high degree of selection is exercised and a pulse to picture ratio of several 100 to one is maintained.

The 15-inch chamber is the most recent and at this time is still in the stage of development. This chamber, we hope, will ultimately be capable of pulse rates from 45 to 60 times a second, making it feasible to take several thousand pulses per picture. The 15-inch chamber has a superconducting Helmholtz coil which provides an 18 kG field and has what amounts to a 120 degree beam entrance window, with a beam exit window of the same aperture.

Since even the 40-inch chamber with its relatively slow (SLAC standards) pulse rate is fast compared to other known chambers operating in the world we feel that a short description of its operation may be appropriate. This will be followed by a slightly more detailed description of the 15-inch chamber.

40-INCH BUBBLE CHAMBER DESCRIPTION AND DYNAMICS OF OPERATION

Figure 1 shows a cross section through the chamber and, starting from the right side, one sees the chamber glass and chamber body surrounding the liquid with the heat exchanger on the top. Proceeding to the left is the piston and

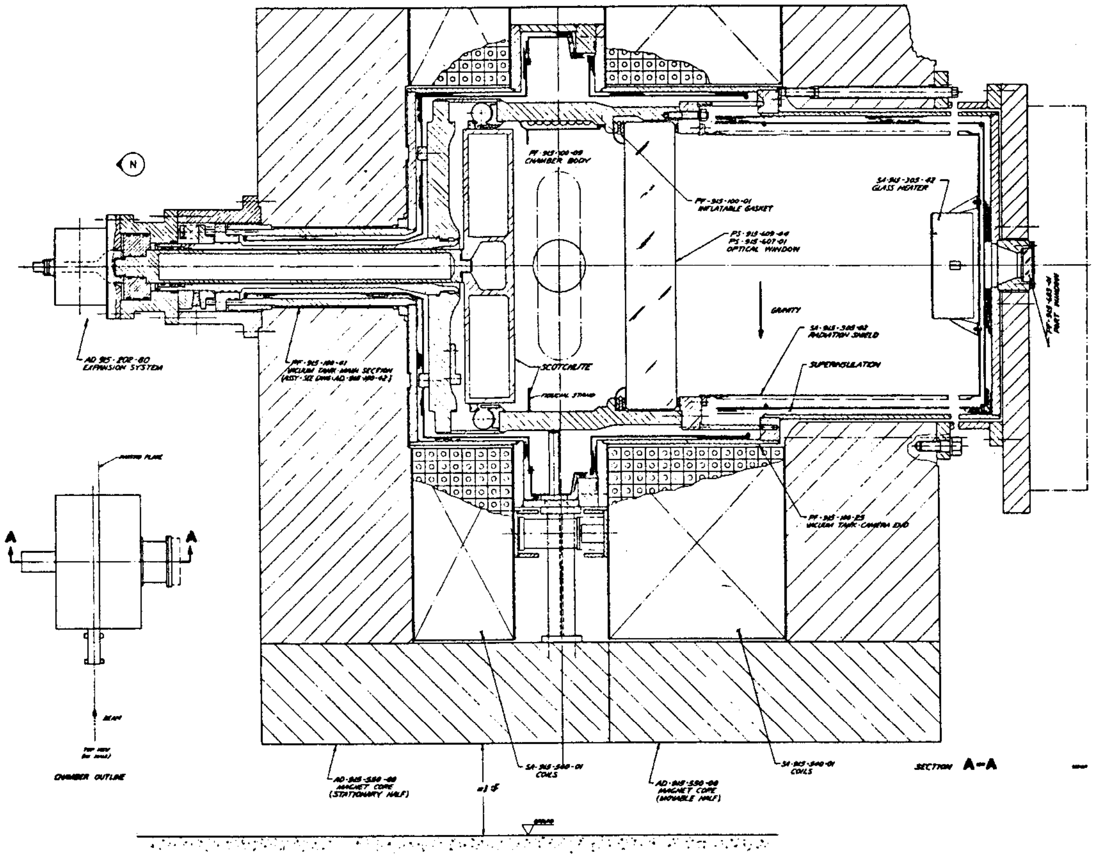

FIG. 1--40-inch bubble chamber cross section.

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†Work supported by the U. S. Atomic Energy Commission.

(Presented at Internat'l. Conf. on Instrumentation for High Energy Physics, Frascati, Italy, May 8-12, 1973)

bellows which complete the liquid containment. The drive rod extends to the left of the piston and out through the vacuum tank and magnet where it is connected to the various drive components to be described later.

In order to pulse at 10 pps a large amount of work had to be done on problems such as pluming from small apertures, leaking valves, bubbles in the bellows, etc. Most of these problems have been solved; the bellows has a heat exchanger within its confines, pluming around the indium glass seal was solved by a new configuration of the indium itself and leaky nylon seat valves have been replaced by indium seat valves with plugs whose sealing surface is a series of concentric saw tooth ridges.

We found that, when running at high pulse rates, one can do very little to correct a runaway condition such as a bubble of hot gas in the top of the chamber and great care must be taken to have all chamber surfaces about at the chamber liquid temperature and this must be the case before trouble develops. Our internal heat exchangers actually do very little work since the chamber casting is the highest part exposed to the liquid and its temperature must be maintained at the proper value or operation is not possible. An ideal heat exchanger would be part of the chamber casting itself and not attached to it and hanging out in the liquid.

Another important requirement to pulsing fast is an expansion system which will do so and with a reasonable degree of reliability. Figure 2a shows a picture of the expansion system and Fig. 2b shows a cross section drawing of the system configuration.

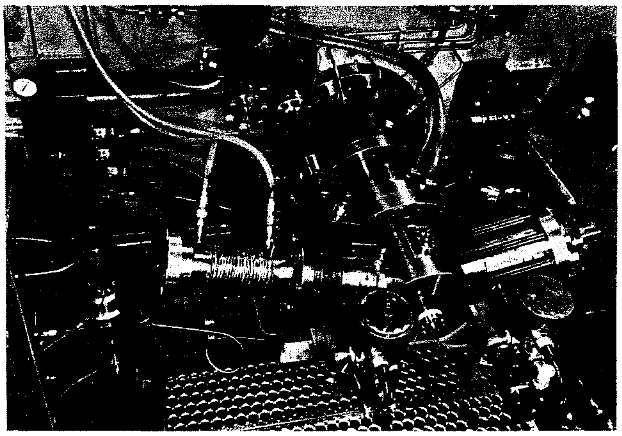


FIG. 2a--40-inch bubble chamber expansion system.

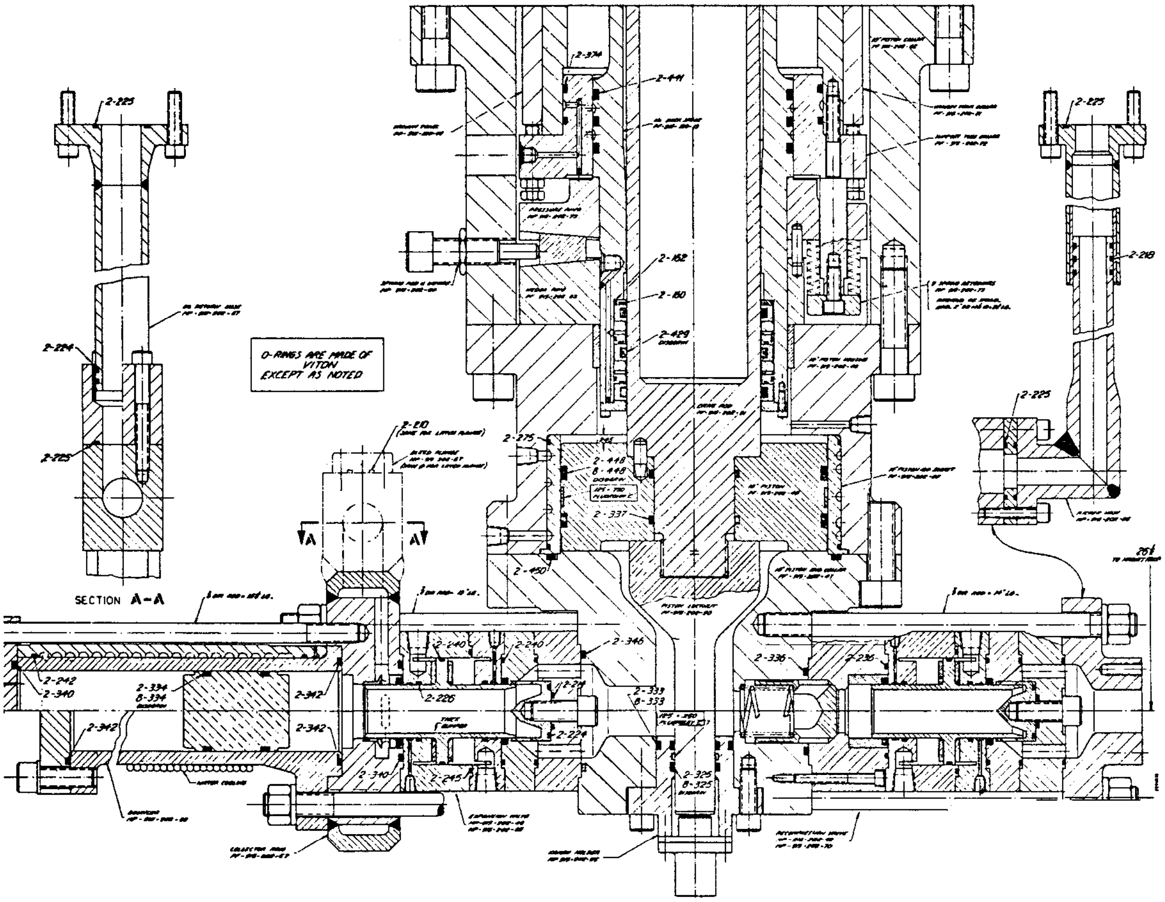
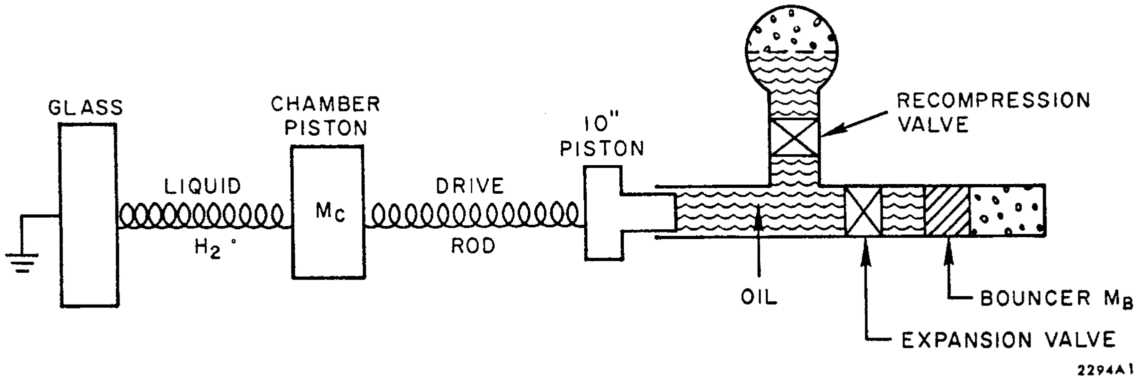


FIG. 2b--40-inch bubble chamber expansion system cross section.

The expansion mass spring system is shown in Fig. 3 and the equations of motion are below the drawing.



$$\ddot{X}_C = \frac{1}{M_C}\left[-K_C X_C + K_2 X_B\right]$$

$$\ddot{X}_B = \frac{1}{M_B}\left[K_3 - K_4\dot{X}_B - K_5 X_B + K_2 X_C - K_7(\ell_0 - X_B)^{-\gamma}\right]$$

FIG. 3--40-inch bubble chamber mass spring. Where the various ks introduce spring constants, friction loss and initial conditions.

The system is a resonant one which has as its component parts, the chamber liquid as the driving force; the chamber piston which is coupled by the drive rod to the 10-inch oil piston and is, in turn, coupled by an oil column through the expansion valve to the energy storage device or bouncer, as it is called. The bouncer is an air spring and 10-lb piston which stores and returns to the chamber piston about two-thirds of the original potential energy of the stroke.

The sequence of events starts with the chamber liquid compressed at about 95 lbs and being held there by the oil pressure on the 10-inch piston. When the expansion valve opens, oil flows from the 10-inch region back to the air bouncer. The chamber piston moves under the influence of the liquid pressure and builds up enough kinetic energy to overshoot, causing a pressure drop in the liquid well below the vapor pressure.

Figure 4 shows a computer solution of the equations and the actual chamber stroke and pressure drop are very similar to the curves shown.

The big trick in a system of this nature is to build the oil control valves so that they are reliable and reproduce their motion with jitter in time no longer than about 50 microseconds. The 40-inch bubble chamber valves (Fig. 5) are

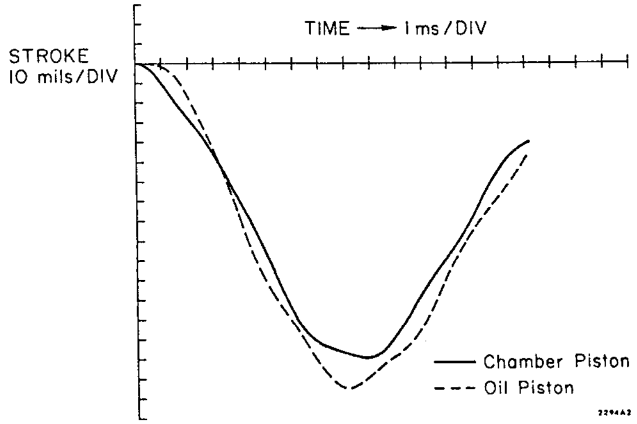


FIG. 4--40-inch bubble chamber chamber stroke and pressure drop.

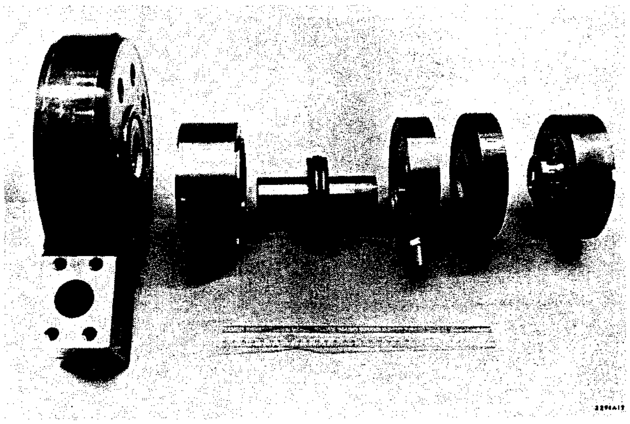


FIG. 5--40-inch bubble chamber valve.

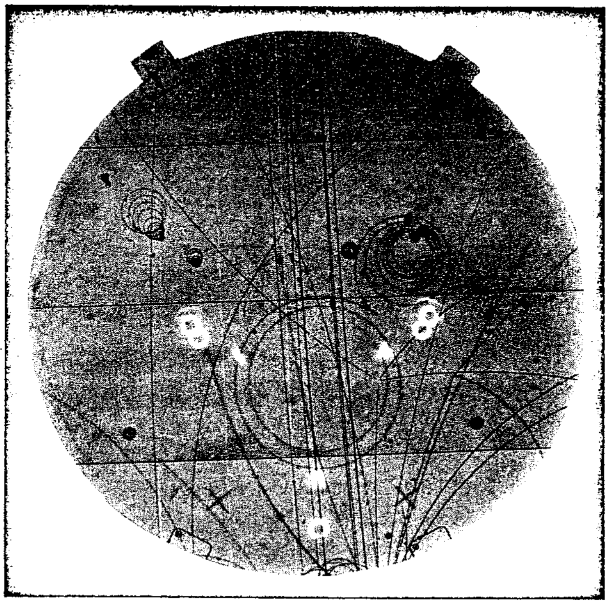


FIG. 6--40-inch bubble chamber track picture.

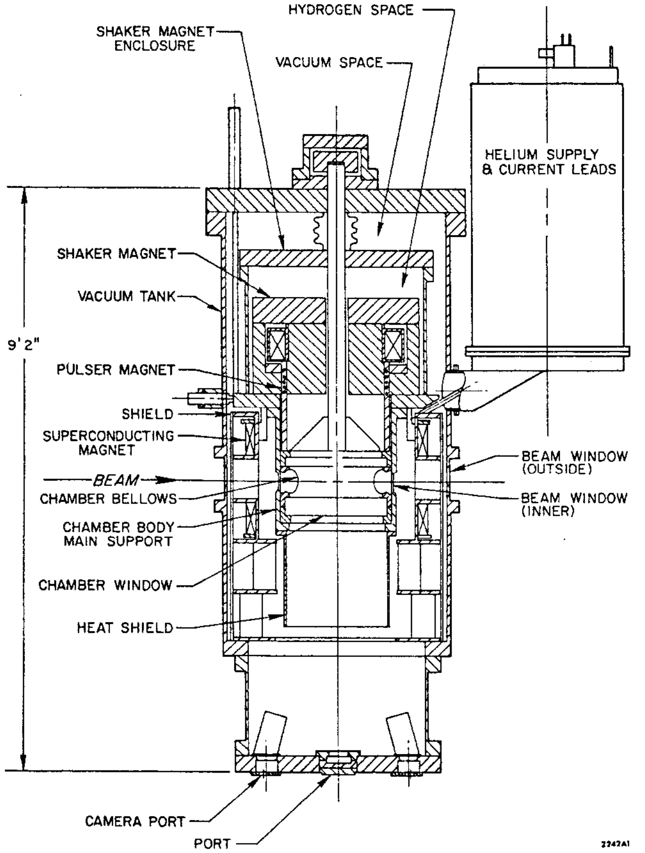


FIG. 7--15-inch bubble chamber cross section.

homemade and extremely reliable and it is common to pulse several million times between maintenance. When the chamber operates it does so without the help of a computer and this is possible because of the resonant expansion system. If all systems are tight with no leaks it is not unusual to pulse several days without adjustment of the stroke.

It is interesting to note that the NAL 15 ft chamber expansion system is a duplicate of the 40-inch system and was built at SLAC by the SLAC Bubble Chamber Group.

The 40-inch chamber will soon be modified to make the exit beam window larger and the iron in the magnet will be opened up to allow easier access for counters at the vacuum tank surface.

Figure 6 is a picture from a recent experiment.

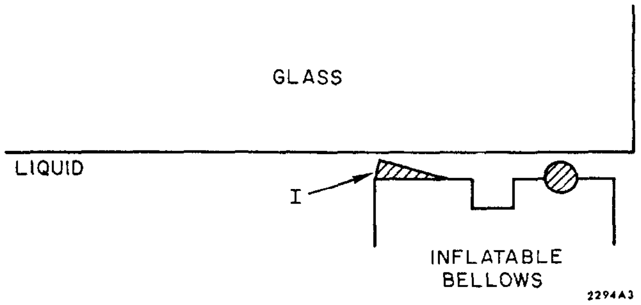
15-INCH BUBBLE CHAMBER DESCRIPTION AND DYNAMICS OF OPERATION

The chamber is perhaps a good deal more sophisticated in nature than any built before, in that it is electrically driven and requires very careful optimization of many parameters for proper operation. This in contrast with the more or less brute force methods of oil-driven expansion systems.

In the early days of the design a good deal of attention was paid to vibration problems. The chamber was to pulse 60 times a second and have components of 120 cycles in the motion. One result of the vibration study is the placement of the dc magnet (Fig. 7), which provides the magnetic field for the moving coil to push against, at hydrogen temperature, in an effort to keep pulse driving forces off of long flexible drive rods. This, of course, brings in lots of problems; such as eddy current heating, in the pulser, which has to be taken away at hydrogen temperature. One problem which has proven to be bad from the operational standpoint is the poor accessibility of the pulser. It is necessary to warm clear up to make a minor repair.

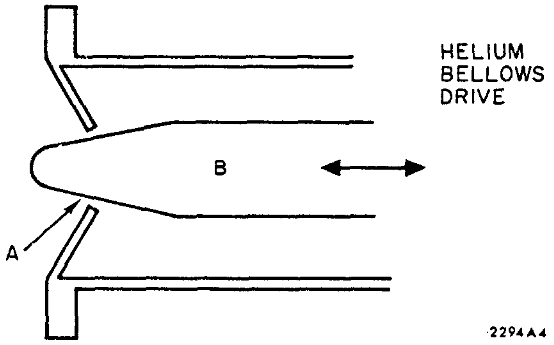
The optical system was originally built as a dual window system with coathangers as reflectors. Although this worked okay from the optics standpoint, it proved to be impossible to cool the liquid and condense a large bubble by conduction through the top glass. A bubble of 6 or 7 square inches in area would take about one minute to condense out. Since the onset of visible tracks and extraneous large bubbles was simultaneous, it soon became apparent that we would have to replace the top glass with a metallic section. Copper would have been a nice choice but the top of the chamber moves up and down in the Helmholtz field and eddy current heating would have been a problem. We compromised on a fabricated structure of one-quarter inch stainless steel with copper inserts for thermal conduction and Scotchlite for light reflection. Our extraneous bubble recovery time is now very short and the problem may be solved.

Extraneous bubbling, a problem at 10 pps, is a catastrophe at 30+ pps and we had to apply the techniques we had learned on the 40-inch to reduce the unwanted bubbles. We used the special indium configuration for the glass seal (Fig. 8) and developed a new, at least to us, valve (Fig. 9) which develops a very high radial sealing force as a result of the warping action of the conical surface. These devices totally eliminate valve pluming and eliminate all but a trivial amount of gasket pluming.



I: New feature is an indium wedge whose base is actually a tinned solder joint to the stainless steel gasket holder. The tinning eliminates voids which plume. The optically polished glass surface mashes the indium with such good contact that no voids are present to plume.

FIG. 8--15-inch bubble chamber new indium glass seal.



A: Cone angle and thickness designed so large radial force results from 100 lbs of force on rod.

B: Rod A286 SS

FIG. 9--15-inch bubble chamber new cold valve.

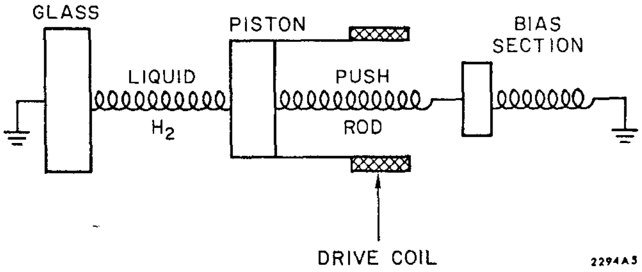
The Helmholtz coil is cooled by liquid helium and produces an 18 kG field. The container for the helium uses the common bubble chamber vacuum and this has proven to be unfortunate. On each cooldown we have had small hydrogen leaks of the magnitude we generally consider trivial, however, with the cold helium temperature surface to act as a trap, we now have to be more careful that we know the H_2 leak rate and can, therefore, decide when we should let the helium go empty and pump off the frozen hydrogen.

The normal boil off rate of the helium is about 6 liters per hour; as we start to pulse this increases to as much as 18 liters per hour. The boil off rate has a maximum at about 12 - 14 kG and drops back down to 11 liters per hour at 18 kG. Normally the eddy current heating should have gone up with increasing field and we attribute this unusual action to the big pieces of iron right above the chamber. By some fortuitous combination of fields from the Helmholtz and the iron the field gradient becomes less where the piston moves and, since the heating goes as this term is squared, we are better off at higher fields.

The total stroke available on the piston is about 125 mils. The actual stroke needed to become sensitive is only about 40 mils, more or less depending on the vapor pressure and overpressure. Since the stress in the bellows (Fig. 7) becomes in excess of 40,000 psi for strokes whose amplitude exceeds 40 mils from the neutral point of the bellows, it is necessary to reduce the return stroke overshoot, if possible, and split the usable stroke one-half to one side and one-half to the other side of the neutral point. Stopping overshoot sounds like an easy thing to do and in principle it is, in practice it is difficult. An explanation of the pulser and dynamics will explain the problem.

Figure 10 shows the spring mass system of the chamber and below it are seen the simplified equations of motion. It is clear from these equations that if one can cause "i" to be a square wave whose duration is equal to the pulse period the chamber will execute a motion described by A(1 - cos ωt) and this is a motion all bubble chamber people like. A square wave of current, however, is not produced by a square wave of voltage because the inductance in the circuit is a factor as is the back emf produced by the coil as it moves through the magnetic field. There are also friction losses involved because the chamber, if left to oscillate freely, will die down to 1/e in about 4 cycles. The net result of these perturbations is that one needs a voltage which is a square wave with a sine wave (back emf) and a decay term added together. The currents involved are 400 amps at 800 volts, so transistor control is out of the question.

We have evolved an expansion system control which more or less does the job, is flexible and adjustable and dodges the problem of exact waveform control.



$$\frac{di}{dt} = \frac{1}{L+L_{1,2}}\left[B\ell\,\dot{X} - \frac{q}{C} - (R+R_{1,2})i\right]$$

$$\ddot{X} = \frac{1}{m}\left[-KX - B\ell i - K_1K\right]$$

FIG. 10--15-inch bubble chamber spring mass system and simplified motion equations.

Figure 11 shows the simplified electrical layout and here one sees a storage capacitor, several inductances in addition to the chamber drive coil inductance and some SCR switches.

The sequence of events during a pulse is as follows.

SCRs 1 and 2 fire which dumps the storage capacitor through inductance L_1 and the chamber coil L. This causes the chamber to move and it does so with a period of about 7 milliseconds. The combination of C, L_1 and the chamber L is tuned so the capacitor has dumped its original charge and reversed polarity as far as it can go $(i=0)$ at the same time the chamber stroke is about three-quarters of the way fully expanded.

When the current tries to reverse SCRs 1 and 2 will cease conduction and the reverse charge will be trapped in the storage capacitor. The chamber continues its stroke through the peak and reverses direction. At about the half-way point SCRs 3 and 4 are fired through coil L_2 and the chamber coil L. The time constant of this system is tuned for a slightly shorter period, about one-half of the other case. Since this is essentially a commutation system, the capacitor is switched end for end and now provides current in the same direction as the original current and this acts as a brake to slow the chamber down and return it to its pre-pulse position. Figure 12 shows the current, stroke and storage capacitor voltage vs time (calculated).

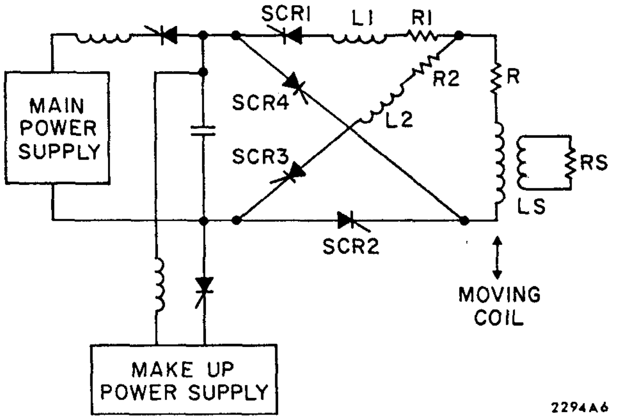


FIG. 11--15-inch bubble chamber electrical circuit.

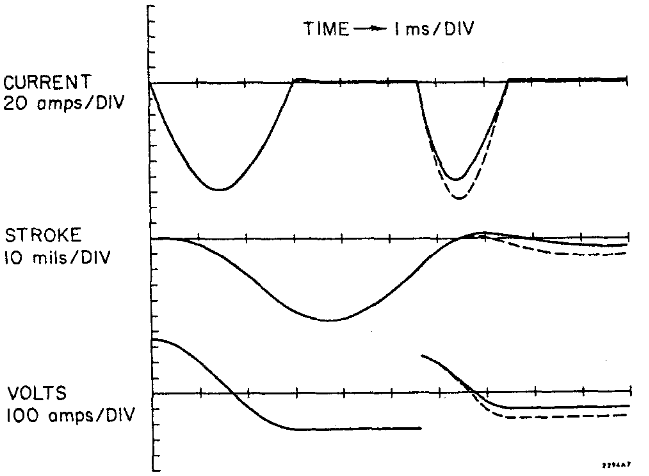


FIG. 12--15-inch bubble chamber current, stroke and storage capacitor voltage vs time.

If the friction losses and the resistive losses are equal, the piston returns and settles out at the original starting point. If they are not equal, the piston can overshoot and oscillate or undershoot and oscillate. In the event that the friction losses are greater than i^2r losses one can put various resistors in series with L_2. Figure 12 shows the effect of this change. If the resistive losses exceed the friction losses, it is possible to shoot a small amount of charge into the capacitor during the "0" current period between the starting and stopping current. Figure 11 shows the make-up power supply.

At the present time we have not been able to match our theoretical stroke with the actual chamber stroke and even a much more comprehensive group of equations of motion predicts a stroke 50 percent greater for a given peak current than we actually achieve with the chamber. At the present time we are unable to account for the difference and suggest that anyone who may hope to make an electrical drive for their chamber proceed with caution. In the case of a small chamber a discrepancy of 50 percent is not important, but for very large fast cycling chambers, it would be embarrassing.

The SLAC chamber has run 45 pps with the above pulser configuration.