Title

PINCH TECHNIQUES AND MEASUREMENTS

Authors

Baker, William R.

Anderson, Oscar A.

Publication Date

1955-10-12

SECRET

UCRL-3207

DECLASSIFIED

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

BERKELEY, CALIFORNIA

DECLASSIFIED

SECRET

DISCLAIMER

UNIVERSITY OF CALIFORNIA
Radiation Laboratory

Cover Sheet
Do not remove

DECLASSIFIED

RESTRICTED DATA

This document contains restricted data as defined in the Atomic Energy Act of 1954. Its transmittal or the disclosure of its contents in any manner to an unauthorized person is prohibited.

INDEX NO. UCRL-3207
This document contains 21 pages
This is copy 3 of 4 series B
Date

Issued to Information Division

SECRET

Classification

Each person who receives this document must sign the cover sheet in the space below.

Route to	Noted by	Date	Route to	Noted by	Date
Lawrence					
Patent	Eng.				
	L. B. McRae	9-10-56			
Info. Div.					
D Brown		MAR 10 1959			

RL-220

PINCH TECHNIQUES AND MEASUREMENTS

by

William R. Baker and Oscar A. Anderson

University of California Radiation Laboratory
Berkeley, California

A series of experiments at Berkeley with the linear pinch method of heating deuterium gas is described. Several factors affecting neutron production by this method have been empirically determined that have resulted in a present operating level of 10^7 to 10^8 neutrons per pulse. A theory based on shock waves is presented to explain the results.

I. EQUIPMENT AND PHILOSOPHY

The work in linear pinch that has been conducted by the Experimental Electronics Group at Berkeley for the past year has centered mainly around some rather simple concepts.[a] We chose to pursue two parallel but quite different paths. One of these was an intensive investigation of ways and means to achieve the rather stringent conditions as laid down by Rosenbluth and others in theoretical work on the pinch method of producing a controlled thermonuclear reaction. This work is still very active and involves the use of water as the dielectric material for the energy-storage system and in the development of a suitable switch for the several hundreds of kilovolts and hundreds of kiloamperes that are expected to be produced by it. Some results from this line of effort may be available in time for the next general Sherwood conference.

The second line of effort was based on the feeling that perhaps the job wasn't quite as difficult as the simple theoretical picture would indicate. This dual line of effort had once before paid off very well in the matter

[a]Experiments on controlled thermonuclear reactions using the linear pinch were carried out several years ago at the University of California Radiation Laboratory. After James Tuck had advocated the linear pinch as one of the best hopes for controlled thermonuclear reactions and after he had carried out some work with the Columbus machine at Los Alamos this approach was resumed at UCRL.

of a pulsed electrostatic deflector system for the 184-inch synchrocyclotron. We designed two systems simultaneously: one that would do the job as per requirements of simple theory (almost impossible in practice) and the other that simply made the most out of the best existing commercial components. We never had a chance to finish the difficult approach, as the simple system was operating while the other was still in design.

So, with this and other similar experiences as incentive, we gathered together 25 Cornell Dubilier 0.5 μf 50-kv condensers that were in the laboratory storeroom from a previous job involving pulse-type condensers and constructed what we thought was a reasonably low-inductance assembly. The number was set by the quantity on hand at the time together with some simple calculations of the energy that we would probably need. A good deal of our future noise problem was eliminated at this point by complete enclosure of the assembly with a metal shield. Protection of personnel from a possible explosion of one of the condensers was insured by a 3/4-in. plywood box backing up the metal shield.

Another guiding principle was convenience. We sacrificed a lower inductance just to make it possible to try a lot of experimental pinch tubes easily. Furthermore, instead of bowing to the view that we would be better off circuitwise to bury the tube inside the condenser assembly, we brought it out so that measuring equipment could be placed within two or three inches of the regions of interest; namely, the center of the tube and one end.

One other feature should be mentioned. We looked upon this experiment as having a little in common with an optical system in that reasonable symmetry in the pinch tube and the energy-storage and switching arrangement was observed. It was felt that a smooth copper pipe in close proximity to the pinch-system insulator would best serve this purpose. We resisted the luxury of boring big holes in this conductor for view purposes, and even now don't know if anything larger than 1/8 in. is bad or not. This fear of upsetting symmetry led to the use of the pinhole camera and Kerr cell technique that has been mentioned in a previous report by J. Riedel.

Unfortunately, we did not give enough attention to the vacuum system and factors affecting purity of the deuterium gas until quite recently. We were very lucky to have been able to obtain measurable results in spite of the early use of undersized vacuum pumps, rubber hoses, plastic, glyptal, etc. We did manage to avoid the use of grease on the many rubber-gasket joints in the system. With our present knowledge of the extreme importance of heavier-element contaminants it seems remarkable that some of the earlier tubes worked at all.

From the beginning, it was never expected that the simple approach to the pinch problem would do more than serve as a guide to the solution of the many problems that would come up in the high-level water-dielectric system mentioned before. So, for the first three months we made a series of studies involving measurements of circuit parameters and pinhole-camera views of the light from pinches in various gases at various pressures and operating voltages. A good deal of work was done with helium because of its nearness to deuterium and the usefulness of the 4686 Å ionized helium line in measuring pinch temperatures. Slowly, we built up a feeling for the factors involved, and by discussions with others in the Sherwood program, such as Post, Colgate and Bostick, the equipment worked better and better and our enthusiasm grew stronger. Finally, after a long spectroscopic study by John Howard had disclosed that our helium pinches were of the order of 500 to 1000 volts temperature we decided to switch to deuterium and look for the neutrons that would be produced from a d-d reaction.

Previous work with an early water-condenser system had disclosed the importance of the gamma-radiation problem arising from the initial ionization phase, therefore, so as not to be confused by it, we designed a special lead-shielded neutron detector consisting of an outer 2-in. shell of lead and a central 2-by-1-in. europium-activated lithium iodide crystal surrounded by a 2-in.-thick paraffin moderator. The very first time that this monitor was put in service it registered the presence of neutrons.

With neutron radiation as a guide, progress was rapid. Many factors were quickly optimized that before were only set indirectly. We soon abandoned rubber hoses in the gas and vacuum lines in favor of copper tubing. A long period of five minutes between pinches for maximum production was cut to two minutes by water cooling and later to thirty seconds and less by thinner insulator walls. We were just beginning to appreciate the role of contaminants, however.

Our first test station by this time was so overloaded with experiments that a second similar system was set up. A slightly different method of wiring the condensers resulted in a one-third lowering of the inductance without sacrificing the convenience of the first system.

Special noninductive shunts to allow oscilloscope readings of large currents had been developed many years previous to this work and were put to good use on our tubes. Certain details concerned with the changing inductance of the pinch-tube system during an operating cycle were very useful. However, since two-thirds of the total inductance of the over-all system was in the condensers and spark-gap switch, and hence unvarying, the detail was not as good as we wanted. The voltage across the pinch tube itself should have much better detail, so we designed a special voltage divider as close to the tube as possible by using the cooling water itself as a potential divider.

Studying voltage signals proved very fruitful indeed. It was quickly noted that the inductance did not vary for approximately the first half microsecond. This, we surmised, had something to do with the current's hanging up at the pyrex insulator wall for a surprisingly long time. The insulator material then came under question. Also, we suspected that gas on the wall first had to be knocked out by the discharge before pinch action could occur. It was further noted that special firing sequences of high and low gas pressure and voltage would give much better neutron production but not consistently so in different tubes or even in the same tube on different days.

A study of other materials was made and the field narrowed to three: beryllia, alumina, and quartz. We constructed a system using quartz. The very first pulse in this tube saturated our counting equipment, and when we finally moved the crystal detector far enough back to get our bearings we found we had gained more than a hundredfold in level. The next thing that we noted was different was the complete absence of the wall hang-up effect; pinching started almost immediately. Much more detail appeared on the voltage signal--so much detail, in fact, that several months later we are still trying to understand the factors behind it.

With so many neutrons to work with we again optimized the various factors over which we had control. The gas pressure went higher than with pyrex. Various diameters of quartz tubes were tried, and then various lengths. Our "standard" length of 18 in. was held constant for the diameter study and then we tried a system 36 in. long by 2 in. This latter surprised us by setting a new record of more than 10^8 neutrons. A shorter 12-in. tube, which we called "Stubby," also surprised us by its erratic behavior. Out of several dozen shots of essentially no production it would give a moderately good one. We thought that the answer to this length difference lay in the ionization of the gas. Since most of the system inductance initially is in the condensers and not in the pinch tube we reasoned that the voltage gradient in the gas initially would be much different with length but that the total time to pinch would not be greatly affected. A simple one-mil nichrome wire current-delay scheme that we added to Stubby seemed to bear this out by making this tube a good producer on every shot. The series 4-in.-long wire would explode and transfer to a low-resistance spark path in one to two microseconds. It was felt that longer time for ionization could not be tolerated because of the speed with which the hot gas could release contaminants from the insulator wall. We have several other ideas on how to ionize the gas, but it does not appear to be an easy problem.

Another possible explanation of the length factor is in the ratio of variable to fixed inductance in the over-all pinch circuit. With a long pinch tube on our present system the current can be made to decrease during pinch because of the increasing inductance. A ten-foot tube demonstrated this very effectively in an early experiment. With conditions adjusted to hold constant current during pinch, the "super pinch" mentioned by Rosenbluth may be approached. Conversely, the performance of a short tube might be improved by a lower-inductance condenser and switch assembly.

Figure 1 is a view of the first linear pinch test station at Berkeley. The central section of the metal-lined plywood box contains 25 Cornell

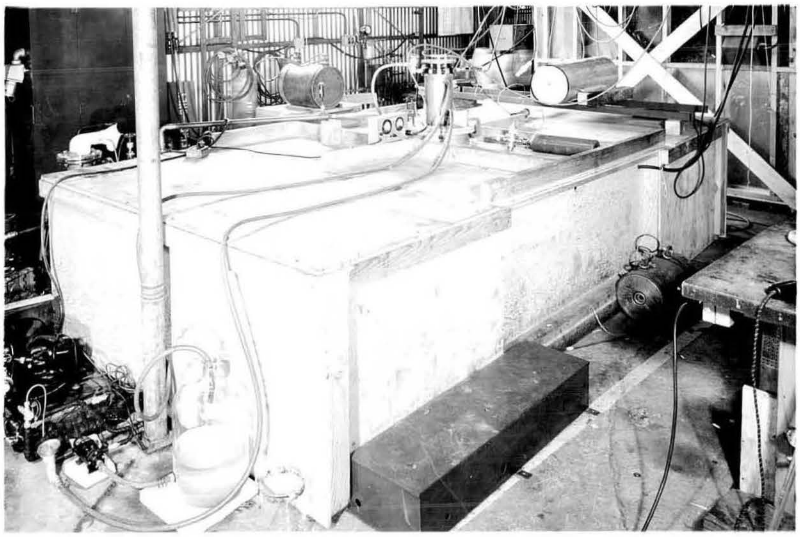


Fig. 1

Dubilier 0.5-μf 50-kv condensers (PL-32-726A). These condensers have been operated for approximately a year in this station at up to 70 kv with only one failure. In the center of the condenser box is a typical pinch-tube experiment. A spark gap actuated by a 9-in.-diameter sylphon bellows (not shown) connects the tube to the condensers pneumatically when operation is desired. Deuterium gas from the cylinder near the pinch tube is continually fed through a needle valve to the tube and measured by a thermocouple gauge. This gauge was calibrated against a McLeod gauge. A copper tube connects the 20-liter two-stage Kinney forepump to the tube. A refrigerated baffle in the forevac line reduces the backflow of oil vapor to the pinch tube during stand-by periods when the deuterium gas is shut off. Pumping is continuous just as gas flow; however, in spite of the constant flushing action the deuterium in the bottle lasts several months.

The rubber hoses shown connect cooling water between the pinch-tube insulator and the outer copper return conductor. The water is cooled by a refrigerator and heat-exchanger system in the left foreground and circulated by a small centrifugal pump. The lithium iodide neutron detector is between the pinch tube and the window. A screen room to the right contains remote controls to condenser charging and firing, two Tektronix 517 scopes equipped with Land cameras, and also Tektronix 513 and 535 scopes. Signals are fed from voltage and current sources (coaxial shunt shown on top of tube) at the pinch tube by RG9U cables and are led through RG fittings in the screen room wall to the oscilloscopes inside. The screen room is of simple 2-by-4 construction lined with galvanized iron on the bottom half and floor for ruggedness and with copper screen on top and upper sides for ventilation and lighting. This room is 8 by 8 ft but would be more convenient if 10 by 10 ft. Wing tanks on each side of the condenser box contain 25 microfarads at 25 kv each for experiments involving higher capacity.

Figure 2 is an exploded view of a typical pinch tube showing bolted O-ring seal system, aluminum ends, gas inlet, measuring and pumping manifold on the right electrode, copper return conductor and water cooling connections, voltage divider ring at extreme left end of copper tube system, 3-by-18-in. quartz insulator, polyethylene water-sealing insulator sleeve at left of quartz tube, needle valve gas control at upper right, and Kerotest vacuum valve at lower right. With the valve arrangement here it is possible to have pinch tubes pumped after assembly on a separate pumping system and then sealed off and hooked up to our test station so as to eliminate pumpdown time on the latter.

Figure 3 shows some of the various pinch tubes tried at Berkeley. Upper left is a two-state pinch experiment dubbed "Piggy-back". The idea here is to use ordinary slow (inductive) condensers in a large-diameter (here 6 in.) pinch tube so that by the time the current reaches a high value the pinch wall will have moved in to the central region where the large current can then be switched suddenly through the smaller pinch system and give a very fast energy transfer to the fresh gas in the latter.

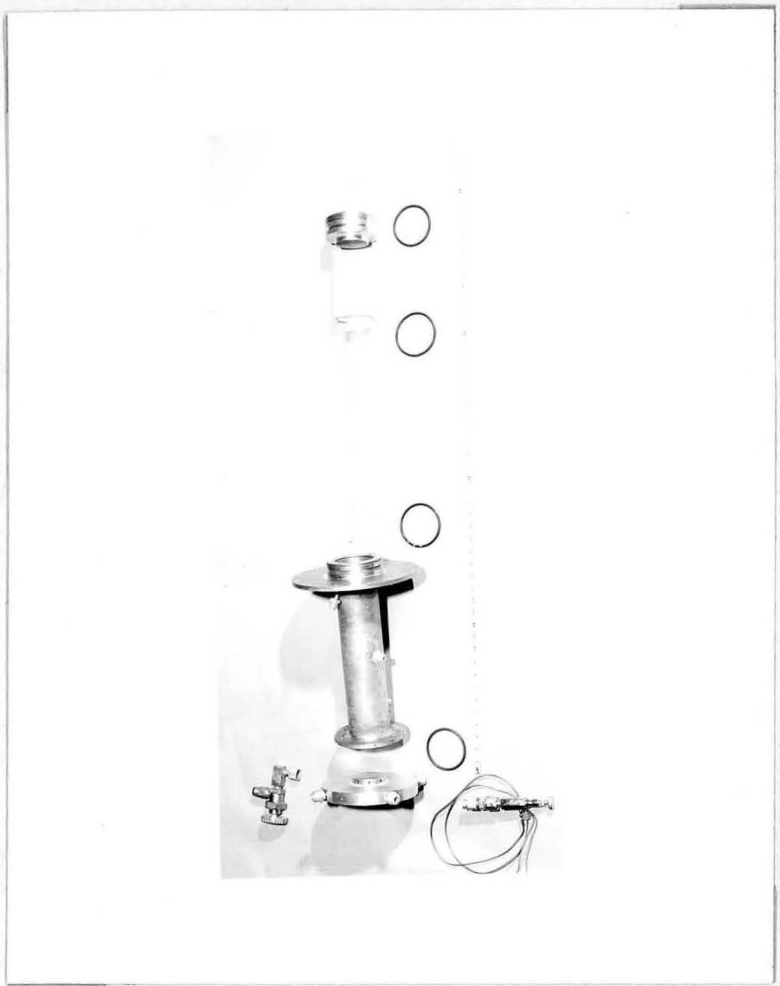


Fig. 2

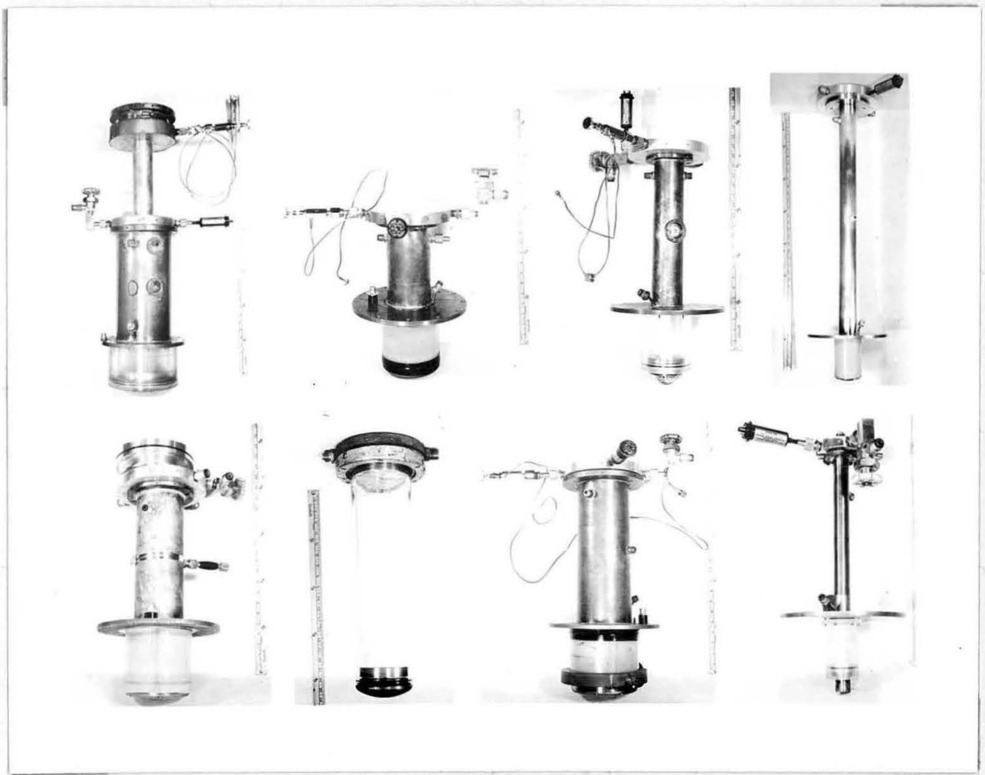


Fig. 3

Piggy-back also disclosed interesting information on pinch-trapped magnetic field. The second tube in the upper row is "Stubby", the 3-by-12-in. erratic type mentioned earlier in the text. The third is an 18-by-2-in. system that the technicians dubbed "Hot Shot," since it was the first tube to give more than 10^7 neutrons/pulse. Fourth is a 36-by-2-in. system that was built primarily to plot axial neutron distribution and settle the question of whether neutrons come from the end or not. It answered many such questions and surprised everyone by being better than any previous tube at up to 2×10^8. At the left in the lower row is an experiment with an end pinhole. We hoped to make measurements with the built-in image converter shown, but light levels and converter sensitivity did not permit this. Other interesting results did come from it, however. Second in the lower row is one of the latest experiments, known as "Lighthouse." Here the pinch discharge takes place up the center of the inner 2-in. quartz tube and returns through the gas between the inner and outer glass walls. By this means we maintained symmetry similar to that in the copper-pipe return system and at the same time secured complete visibility of the inner pinch action. This scheme has worked excellently, and many interesting experiments are being scheduled for it at present. Third is the 4-by-18-in. experiment. The last tube is 18 by 1 in., the limit to which we have gone in small size.

II. EXPERIMENT AND THEORY

The chief experimental tools are the fast plastic scintillator, the slow crystal scintillator, the current shunt, and the voltage divider, all described in Part I. Most of our knowledge of the pinch mechanism has been obtained from the plastic scintillator and the voltage divider.

The voltage divider gives us the electric field inside the pinch tube with a good transient response characteristic for all signals except those that change very rapidly (times in the order of 10^{-9} second) or very slowly (10^{-4} second). At high gas pressures the voltage breakdown, once it starts, is very fast, and excites a damped high-frequency oscillation in the divider which can be noticed in some of the pictures in this report. The other (low-frequency) effect is negligible over the duration of all the voltage pictures shown.

We obtain and study the voltage wave forms under various conditions and try to deduce the motions of the gas in the pinch tube. When the current sheath contracts or expands an electric field is generated, so that the appearance of the voltage wave tells us something about the motion of the current sheath. Information is then gained about the motions of the gas. (For a picture of the current sheath, see Marshall Rosenbluth's report from the February Sherwood meeting.[1])

The voltage signal, if we neglect resistance, is produced by $L\dot{I}$ and $I\dot{L}$. The current wave forms have shown us that the $L\dot{I}$ term must be of secondary importance except for the early stages of the pinch. For simplicity we assume that we have $E = I\dot{L} = -10^{-8}\, I\dot{R}/5R = -10^{-8} H\dot{R}$ (E and L are per cm). For a positive current, a positive voltage means that the sheath radius R is decreasing with time, i.e., $\dot{R}$ is negative. The voltage E is zero in this approximation if $\dot{R}$ is zero and negative if the sheath is moving outwards. At a given radius R and current I the voltage is proportional to the velocity $\dot{R}$. With $\dot{R}$ constant, the voltage depends on I/R, i.e., on the surface field H. Any sudden change in the voltage should not be due to a sudden change in I or R but to a change in $\dot{R}$. If, for example, the voltage suddenly jumps from a positive to a negative value, the velocity must have suddenly reversed direction. Such voltage jumps are prominent in our Berkeley pinch experiments.

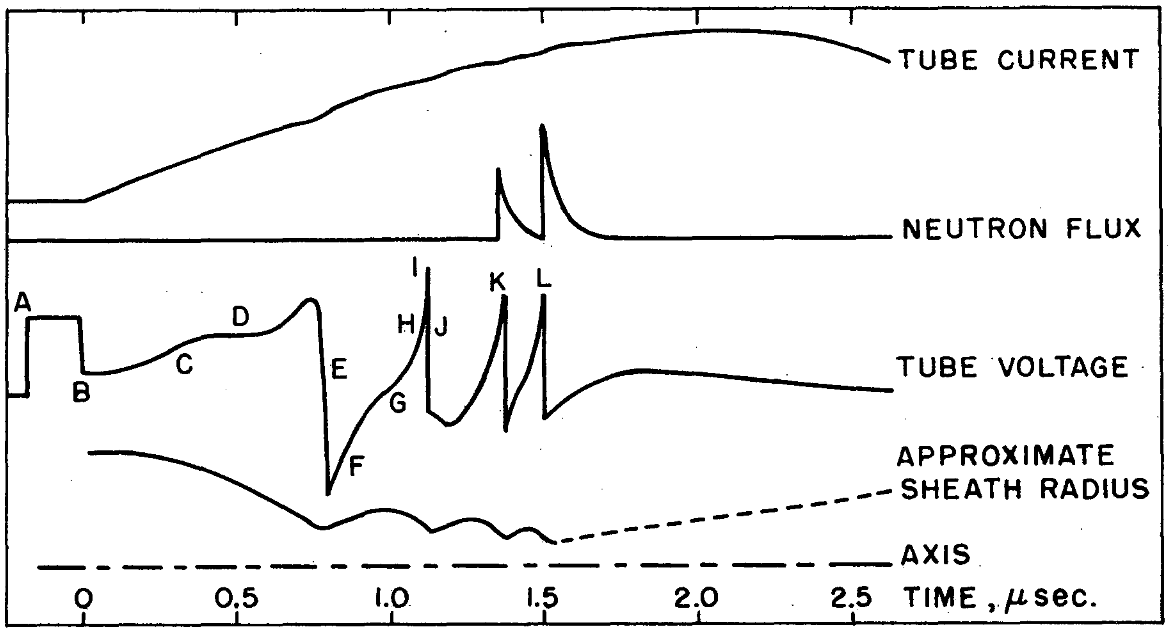
Stirling Colgate of the Livermore Radiation Laboratory gave us our first clear explanation of these voltage jumps, has kept us up to date theorywise, and has helped us in many other ways. J. J. Tiemann, now at Stanford, recently became acquainted with our work and has given us an independent analysis based on a different viewpoint, predicting higher temperatures but with essentially the same results otherwise. Whereas Colgate's analysis stresses shock-wave dynamics, Tiemann's stresses free-particle dynamics. Both are important. In the pinch, the Rutherford-scattering mean free paths are short initially, but are lengthened as the fourth power of the increasing velocity. There is a transition, then, from shock-wave dynamics to free-particle dynamics at some point in the pinching action. The exact over-all picture is difficult to obtain, but fortunately either type of dynamics used alone gives the same general picture as the other.

In Figure 4 is a sample sketch based on several actual photographs of voltage waves. This will be analyzed with both of the above viewpoints in mind. For simplicity the work <u>shock</u> will be used to mean energy transfer either by a series of collisions or by free particles. The key letters A, B, C ... in the following description refer to the key letters in Fig. 4.

The details up to (J) are reproducible for any tube under given conditions, although they vary from tube to tube and according to pressure, voltage, and nature of gas. From approximately (J) on, the wave form varies considerably from one shot to the next. This would be expected on the basis of shock-wave or free-particle theories, since any small variations in the intensity and shape of the early shocks will be magnified as time goes on. In the set of photographs from which the sketch was made, the fourth bounce was as drawn on some, and poorly defined on others. With one tube (4-by-16-in. quartz) the fourth bounce was entirely absent and the third appeared only occasionally. Neutrons were produced at the second bound and also at the third, when it showed up. This tube required a relatively high condenser voltage for neutron production. In still other tubes, which were operated at low voltage to avoid breakage, no neutrons were observed until the third shock.

Some of the oscillograms in this report show several voltage spikes crowded together after the second or third shock. Here perhaps, instead

FIGURE 4



(A) Condenser bank is switched to pinch tube. Voltage signal shows full condenser voltage.
(B) Pinch tube ionizes. Voltage falls to level determined by $L\dot{I}$ and resistance term.
(C) Sheath moves in. Shocks are moving ahead at twice sheath velocity, which builds up rapidly with increasing current. Resistance becomes low. $I\dot{L}$ takes on predominance in voltage signal as I and $\dot{L}$ increase.
(D) Sheath overtakes first slow shocks. (These are reflected at twice new sheath velocity minus their old velocity.) Sheath slows somewhat, or at least its acceleration is reduced, depending on conditions.
(E) Sheath meets shock front that has passed through or reflected from Z axis. New sheath velocity is outward, of same order of magnitude as inward velocity immediately preceding. Voltage changes suddenly along with velocity.
(F) Sheath is moving out owing to momentum of outward shock, but is slowing down owing to magnetic pressure.
(G) Sheath velocity is momentarily zero. This is the case at every voltage zero, neglecting $L\dot{I}$ and resistance.
(H) Magnetic pressure is pushing sheath in again and new shocks are created. These tend to be hotter than first set, since current is now larger and radius is smaller, both causing higher magnetic pressure.
(I) Voltage becomes high very fast, since it is proportional to H and $\dot{R}$ and both are increasing rapidly. In some oscillograms, this spike is much higher, even, than shown in Fig. 4. Perhaps sheath meets rarefaction left behind shock thrown off at (H).
(J) Second main shock front causes second bounce. Reversals of velocity and voltage are often faster than at (E).
(K, L) Third and fourth bounces.

of the simple mechanism described, with a series of shocks numbered 1, 2, 3, 4, ..., there is a sort of splitting of shock fronts, giving a series numbered something like 1, 2a, 2b, 3a, 3b, 3c, ... The effect could also be associated with one of the well-known pinch instabilities. In any case, we have observed that the amount of neutron production from a given shot almost always correlates with the amplitude of the voltage spikes occurring at the same time. This is reasonable, since the spike amplitudes are, according to the theory already presented, proportional to the shock velocity and compression (1/R). The neutron production is sensitive to both factors.

On all our voltage oscillograms, there is a point (as at (E) in Fig. 4) at which the shock-induced signals cease fairly suddenly. The current at this time continues to rise, at about its former rate. The plastic scintillator signal has indicated that most of the neutron production ceases around this same time. Like the multiple-spike effect, the mechanism here is not yet clear. Instability, again, may be responsible, or a breakdown of the insulating walls. We are still gathering various sorts of evidence to help explain both effects. Since both are associated with neutron production, their control may be important later on in a high-production machine.

III. EXPERIMENTAL RESULTS

The higher neutron yields we have been working for (now averaging up to 10^8 per pulse) have made our attempts to study the neutron production increasingly easier. We have at last succeeded in locating their source, and it is definitely not at the electrodes or in the insulating walls, but in a region of small diameter running the length of the tube.

The axial-distribution study was especially easy, because the tube is much longer than it is wide. We placed two recoil counters against the 2-by-36-in. tube. The photomultiplier signals gave a smooth indication of the neutron flux as a function of time, since about 10^4 scintillations were produced in around 1/3 microsecond by each shot. Light attenuators were used to avoid overloading the photomultipliers. When the two counters were positioned at the same elevation along the Z axis, the output signals were identical. When one was put at the middle and one near either end, the signals showed different time-structure details in a random fashion from shot to shot, but had about the same average amplitude. The leading edges were steep, usually rising to peak value in a few shakes, and started simultaneously with less than one shake time difference. This experiment established the relative unimportance of three suggested mechanisms for neutron production. The theory in these was that migration of positive ions would cause a good part of the applied potential to appear in a starved region at the anode. In mechanism No. 1, the high gradient at the anode would produce a very energetic pinch in this region, with high production there only. In No. 2, ions would acquire high axial velocity in the starved region and then react with deuterium adsorbed at the cathode. Mechanisms Nos. 1 and 2 were shown unimportant by the observed axial uniformity. Number 3 was like No. 2 except that the axially accelerated ions were supposed to react with the gas along the tube instead of at the cathode, giving more uniform neutron distribution. However, these ions would take at least 1/4 microsecond to travel 18 inches, causing the same spread in neutron timing. Our experiment, with a resolution of 10^{-8} second, showed no such effect.

Three experiments with recoil counters established the diameter of neutron origin as considerably less than that of the pinch tube. One involved a constant-width slit in a paraffin block that was used to scan the tube diameter. A second used a variable-width slit with the tube axis kept in the plane of symmetry. The third used a narrow block that shaded the scintillator from the tube axis but not from most of the wall area. All three setups were run against a reference counter, and all three indicated a small-diameter source, probably about 1/2 in.

The present level of neutron production is mainly due to our earlier work, which showed the importance of wall condition and led to our present use of quartz as a wall material. When we were using pyrex, we found that the production depended on the history of operation of a given tube and varied from one tube to another of the same size. Figure 5 shows the variation with one tube according to the sequence of pressure and voltage change from one shot to the next. This processing technique was used for a time as standard practice, but we found later that a different pyrex tube of the same size produced neutrons just as well without it.

Figures 5, 6, and 7 show the difference between pyrex and quartz tubes. Figure 6 shows the first few shots on the first quartz tube. The sequence actually goes from bottom to top. The bottom wave form is from a pyrex tube of the same size. The second from the bottom was taken when the quartz tube was first fired. The pressure for this first shot was set around the optimum for the old pyrex tube. The succeeding pictures, reading upward, show the yield improvement as the pressure was raised. The greater detail in the voltage signal for the quartz tube, indicating more and hotter shock waves than in pyrex, is obvious. Comparison of the wave forms also shows the effect described in Part I, namely the shorter delay in the quartz tube before the voltage rises at the initial pinch.

The crystal counter pulses, as in Figs. 5 and 6, are obtained from moderated neutrons, with the crystal-paraffin-lead arrangement described in Part I. The time base is 50 μsec per division and is of no particular importance except to show that the neutrons come out of the paraffin at about the expected rate. The counter was 1.5 ft from the tube in Fig. 5 and 4 ft away in Fig. 6. The counter was moved to a greater standard distance after each of these landmarks. For a time, while we were experimenting with various quartz tubes of 18-in. length, our standard distance to the counter was 20 ft. After trying our first long quartz tube, we were forced to move it again to the present standard of 63 ft. This

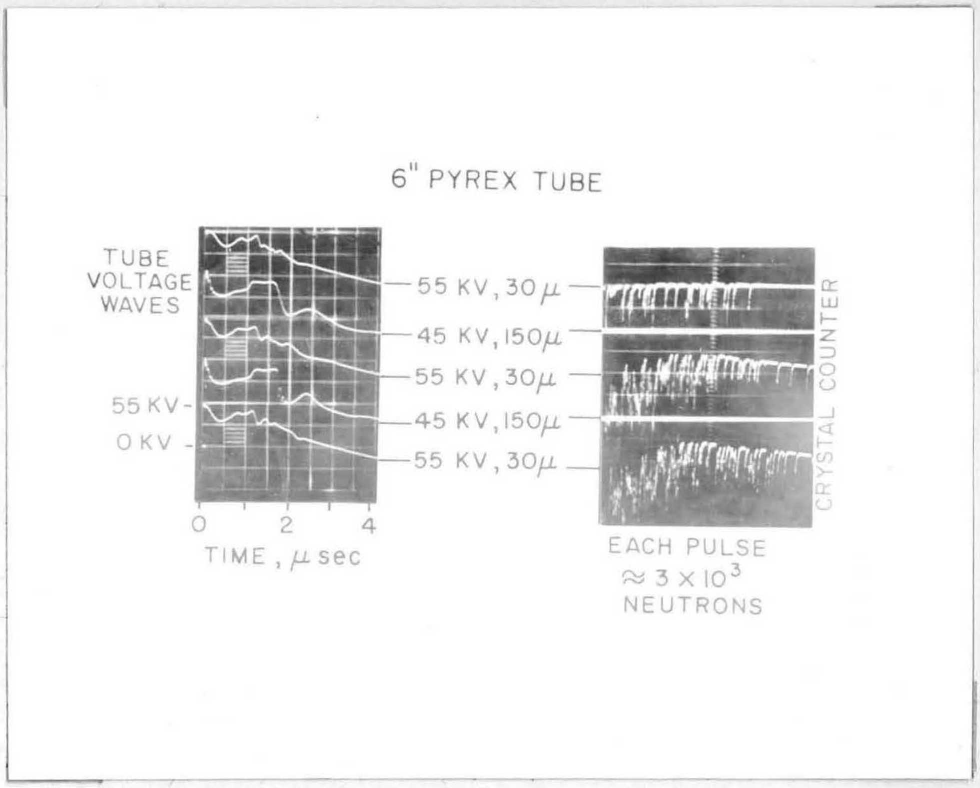

6" PYREX TUBE
TUBE VOLTAGE WAVES
55 KV -
0 KV -
55 KV, 30μ
45 KV, 150μ
55 KV, 30μ
45 KV, 150μ
55 KV, 30μ
0 2 4
TIME, μ sec
CRYSTAL COUNTER
EACH PULSE ≈ 3 × 10³ NEUTRONS

Fig. 5

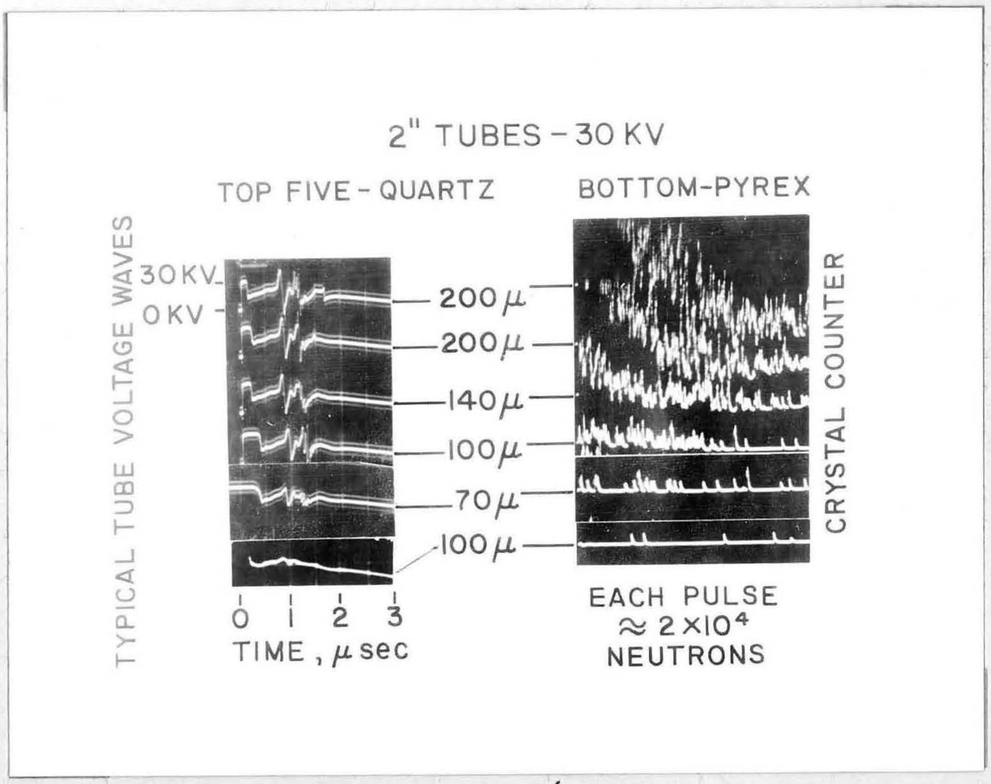

2" TUBES - 30 KV
TOP FIVE - QUARTZ
BOTTOM-PYREX
TYPICAL TUBE VOLTAGE WAVES
30 KV
0 KV
200μ
200μ
140μ
100μ
70μ
100μ
0 1 2 3
TIME, μ sec
CRYSTAL COUNTER
EACH PULSE ≈ 2 × 10⁴ NEUTRONS

Fig. 6

gives about one count per 5 x 10^6 neutrons, and frequently shows several dozen counts per shot.

Figures 7, 9, 10, 11, and 12 show how the voltage wave forms and the neutron production vary with tube size, condenser bank voltage, and operating pressure. The leveling or falling off of production at higher voltages in Fig. 9 seems to be connected with the starting conditions for the pinch. The initial ionization must change, since the ionization cross section varies adversely with voltage at these levels.

Figure 8 charts the optimum pressure, determined as in Fig. 9 against tube size. The optimum pressure is, of course, fairly broad, and this chart should be interpreted accordingly. One could probably draw a straight horizontal line for the intermediate curve (mass divided by radius or pressure times radius) and be close to optimum. The best pressure probably changes somewhat with operating voltage, but it is so broad we have not found which way it goes.

As mentioned in Part II, the neutron yield and the voltage spikes vary together from one shot to the next, in normal operation under fixed conditions. In Fig. 13 we have taken typical examples from experiments where the conditions were changed, and a similar correlation is indicated. In one experiment a long solenoid was wrapped around the pinch tube, and a dc current source was connected on alternate shots. Figure 13 shows how the resulting magnetic field reduced the shock energy and neutron production. In another experiment, also shown, the temperature was reduced by addition of argon as a contaminant. Discharges with pure argon or with deuterium at very high pressure are shown to yield a single weak bounce.

Figure 14 gives the story of our attempt to utilize the stronger and more available refractory material, aluminum oxide. The voltage waves and poor neutron yields obtained initially put the wall surface under suspicion, after our experience with pyrex. We reasoned that if the surface could be made smooth and free from pores, as with quartz, the performance should be comparable. Therefore we melted and sealed the surface by a series of shots with argon (used to avoid any chemical reaction). The predicted results were obtained for a while, with neutron yields not quite as good as with a similar quartz tube, but far better than before and far better than any pyrex tube had given. Unfortunately, as Fig. 14 shows, the effect of the treatment was not permanent. For the time being, we have dropped work with any material but quartz; however, alumina ceramic may eventually prove more satisfactory and, with a little more effort, the surface problem probably can be solved.

Figure 15 shows some pinhole photographs of the discharge in the 4-by-16-in. quartz tube. The pinhole was 2 in. off center in the upper electrode and produced an image on P-11 phosphor in an evacuated chamber above the electrode. Compared with former arrangements in which the light passed through pyrex or quartz, this setup favored the shorter

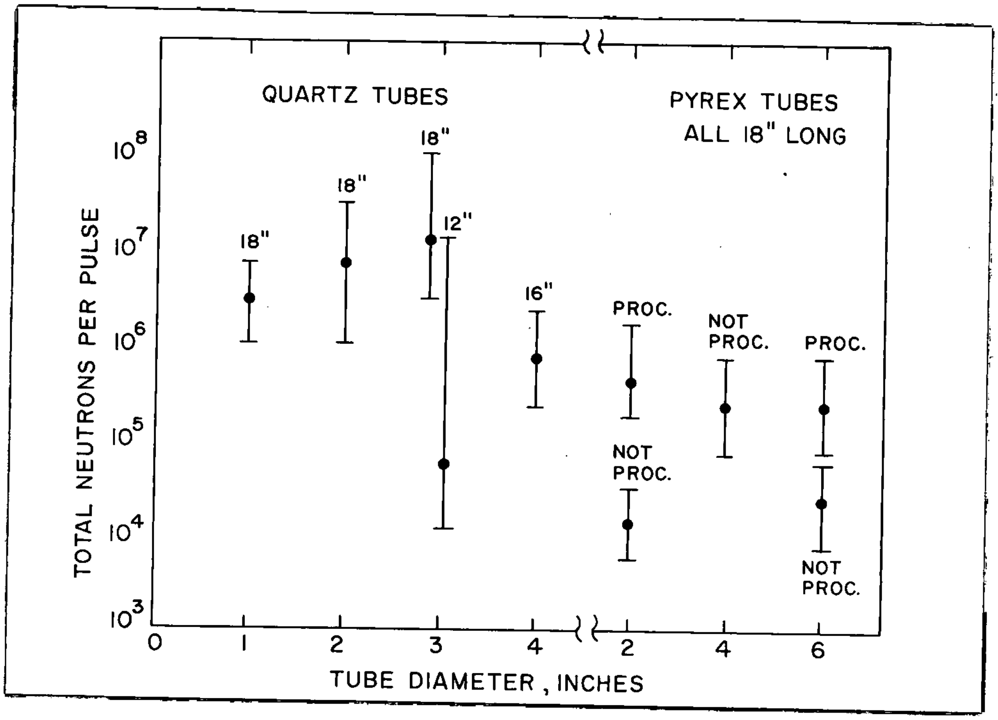


Fig. 7

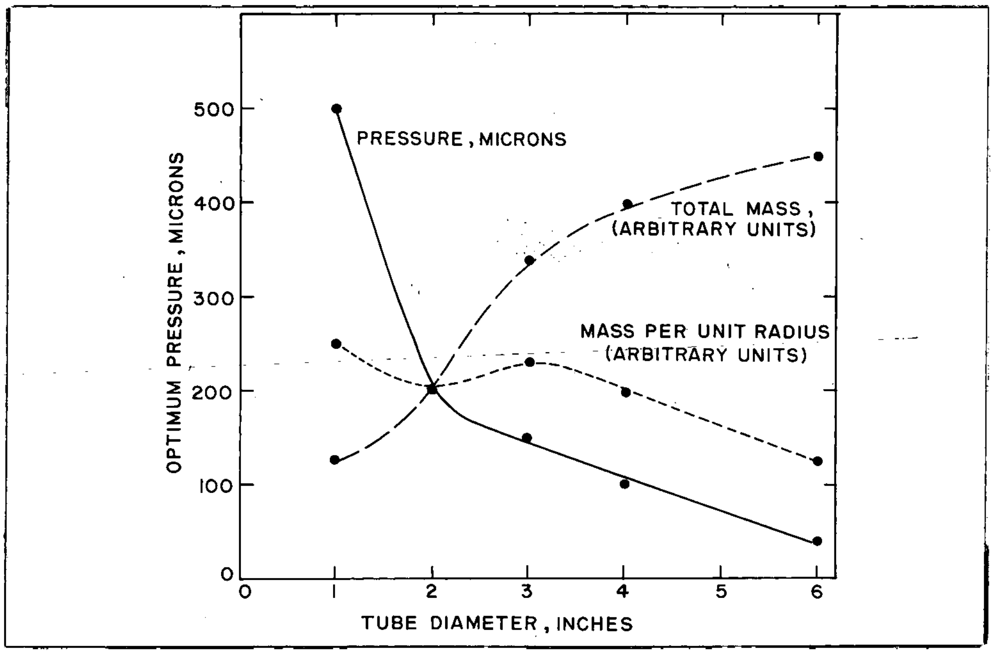


Fig. 8

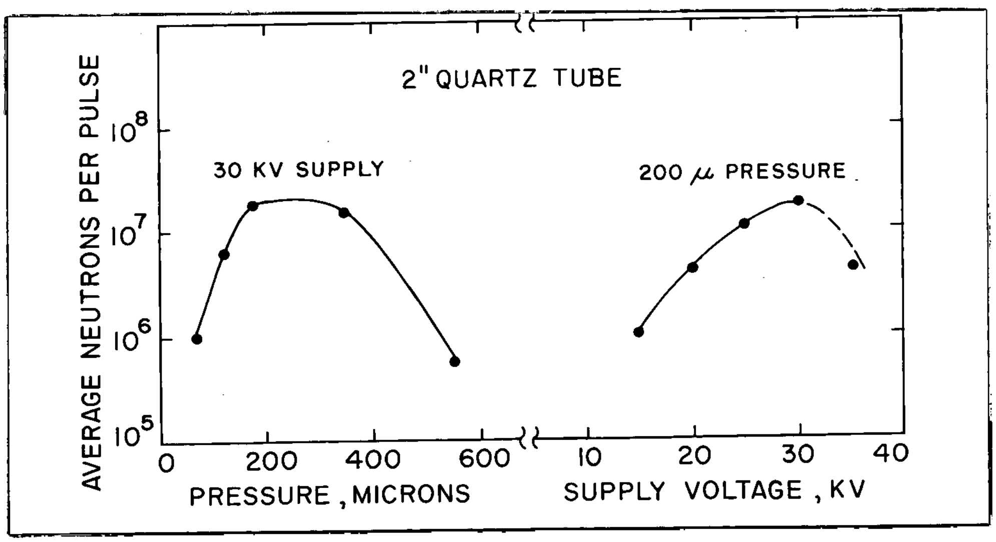


Fig. 9

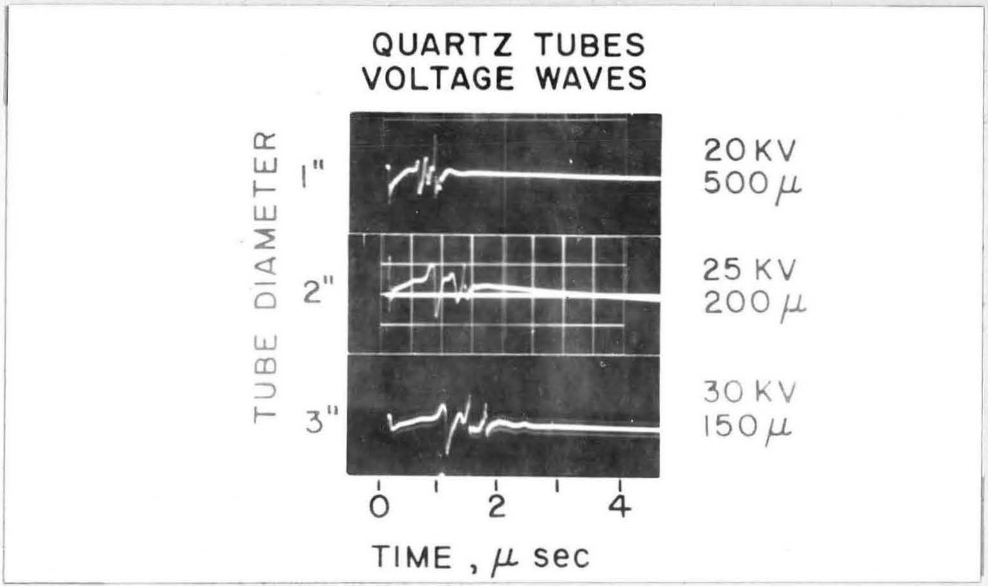


Fig. 10

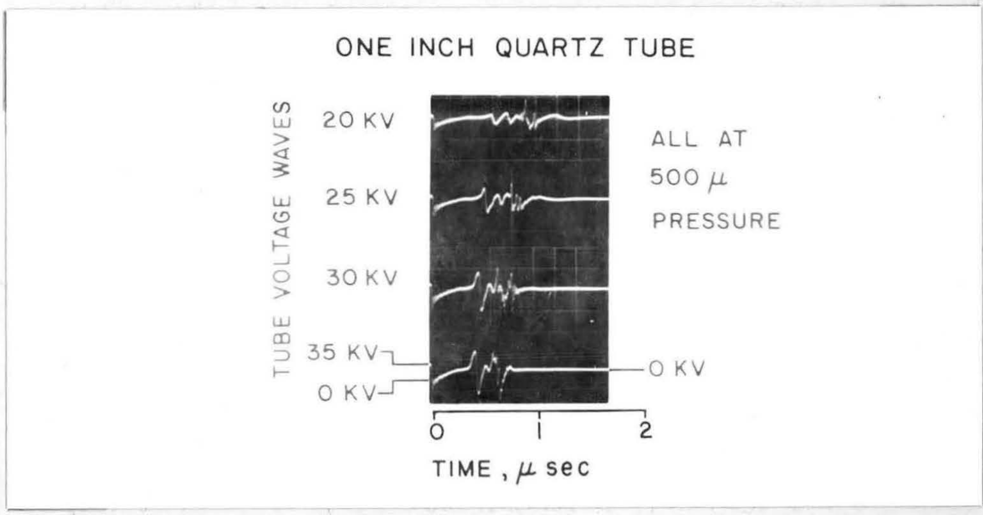


Fig. 11

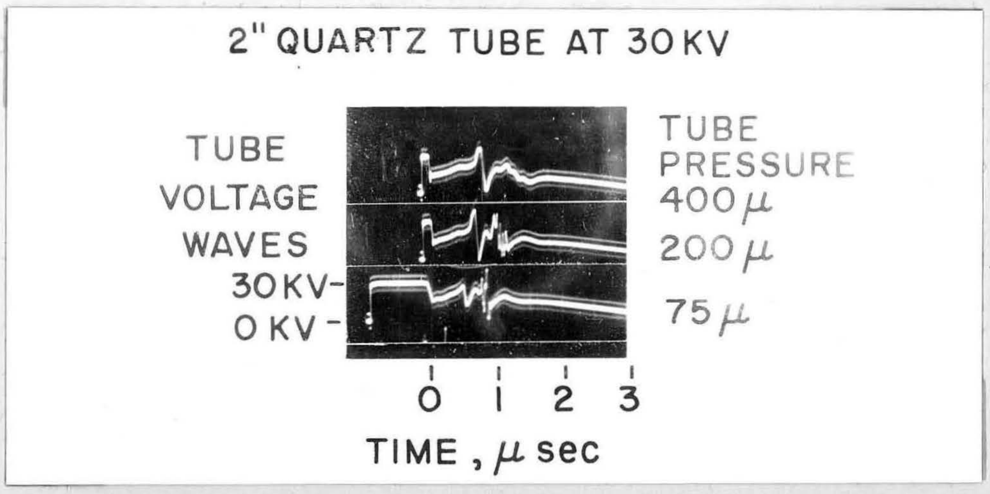


Fig. 12

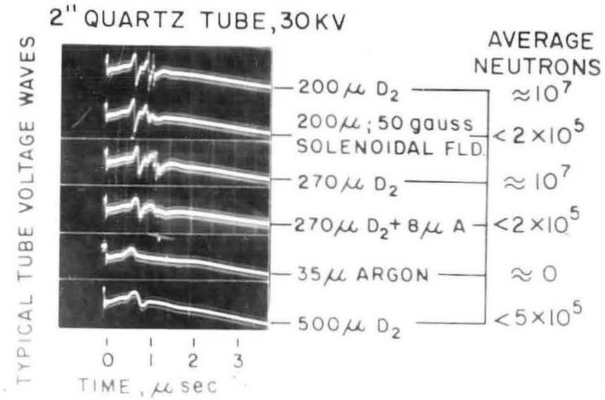

2" QUARTZ TUBE, 30 KV
TYPICAL TUBE VOLTAGE WAVES
AVERAGE NEUTRONS
200 μ D2
≈ 10^7
200 μ; 50 gauss SOLENOIDAL FLD.
< 2 × 10^5
270 μ D2
≈ 10^7
270 μ D2 + 8 μ A
< 2 × 10^5
35 μ ARGON
≈ 0
500 μ D2
< 5 × 10^5
0 1 2 3
TIME, μ sec

Fig. 13

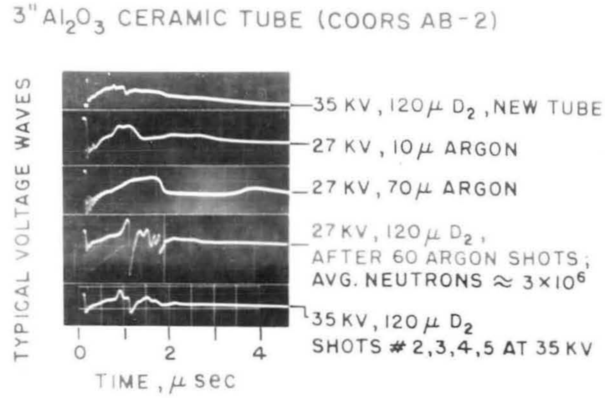

3" Al2O3 CERAMIC TUBE (COORS AB-2)
TYPICAL VOLTAGE WAVES
35 KV, 120 μ D2, NEW TUBE
27 KV, 10 μ ARGON
27 KV, 70 μ ARGON
27 KV, 120 μ D2, AFTER 60 ARGON SHOTS; AVG. NEUTRONS ≈ 3 × 10^6
35 KV, 120 μ D2 SHOTS # 2,3,4,5 AT 35 KV
0 2 4
TIME, μ sec

Fig. 14

wave lengths. Except for the different perspective, however, the pinches looked about the same.

The image was studied with a photomultiplier to determine the timing of the light from various areas. The photomultiplier signal was compared with the voltage-divider signal, which with argon in the tube showed the characteristic single bounce (compare Fig. 13). The light from the bright pinch region along the axis (see Fig. 15) appeared simultaneously with the bounce, and died out in about 1/4 μsec. The light from the spot centered at the far electrode and the general background light started slightly later, peaked in about 4 μsec, and decayed at a similar rate. The electrode spot looked the same with either voltage polarity, i.e., either at the anode or cathode. When we used deuterium instead of argon, there was very little pinch light with voltage and pressure conditions that produced neutrons. The bright spot and the background light were not greatly affected.

Figure 16 shows the recoil counter signal compared to the voltage signal for another quartz tube. The two signals are also shown combined on a single sweep to remove any large uncertainty about the relative timing. The time delay through the photomultiplier is 2 or 3 x 10^{-8} second.

Several experiments were performed recently, too late for detailed presentation here. These included:

(1) Several types of attempts to attain better initial ionization, one of which was described in Part I.

(2) Kerr cell photography of the discharge in "Lighthouse" (see Part I). The pictures showed a great turbulence in the gas, or else a very spotty brightening of the quartz wall, just after the pinches. Another Kerr cell unit is being built to allow stereoscopic views.

(3) Study of the discharge current as a function of space as well as of time in a 3-in.-diameter quartz tube.

Our object was to get an idea of where the discharge current flows when the voltage signal suddenly stops bouncing (see Part II). A special shunt detected only that part of the current flowing in the inner 1.5 in. of the 3-in. tube. The results were: (a) Very little current is inside the 1.5-in. boundary for the first 1/3 μsec of sheath motion. (b) By the time the sheath has contracted to 1.5 in. the full current signal appears. One or two dips in amplitude follow that synchronize with the first voltage and sheath bounces. (c) After the voltage bounces stop, there is a constant ratio (about 1:3) between the inner current and the total current for the remainder of the first half-cycle of total current. (d) The inner current seems to fall to this lower value before the final fast voltage bounces appear, which is hard to explain. If the shunt is at fault, then doubt is cast on (c) at least. To reduce the possibility of

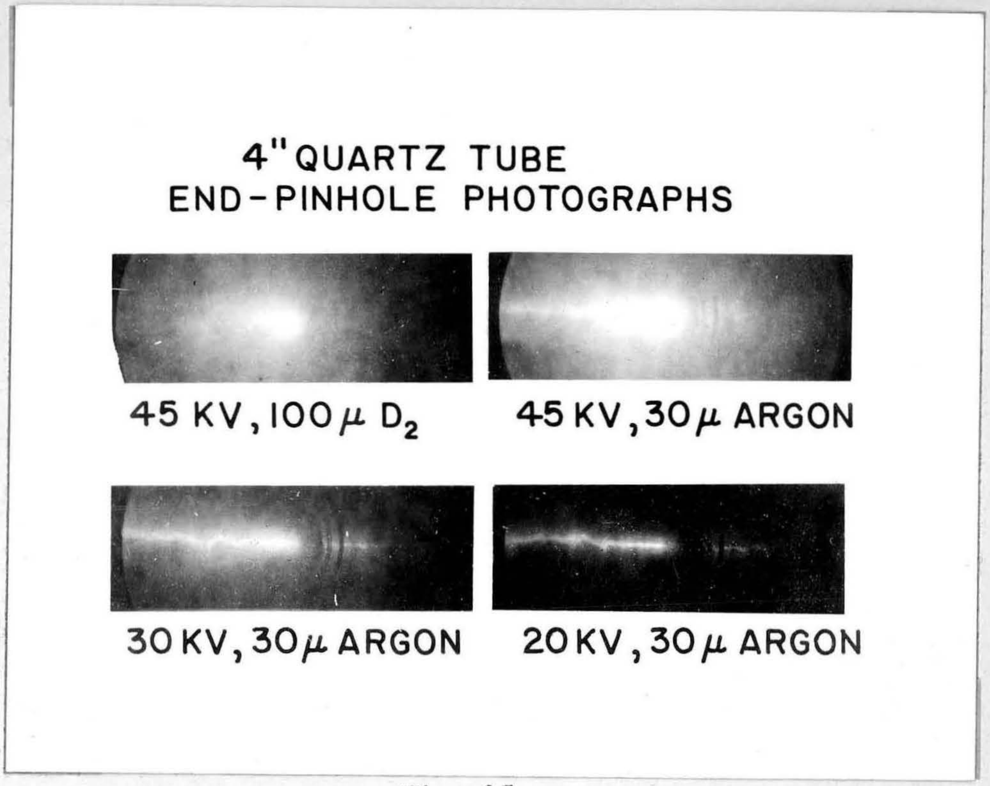

4" QUARTZ TUBE
END-PINHOLE PHOTOGRAPHS
45 KV, 100μ D2
45 KV, 30μ ARGON
30 KV, 30μ ARGON
20 KV, 30μ ARGON

Fig. 15

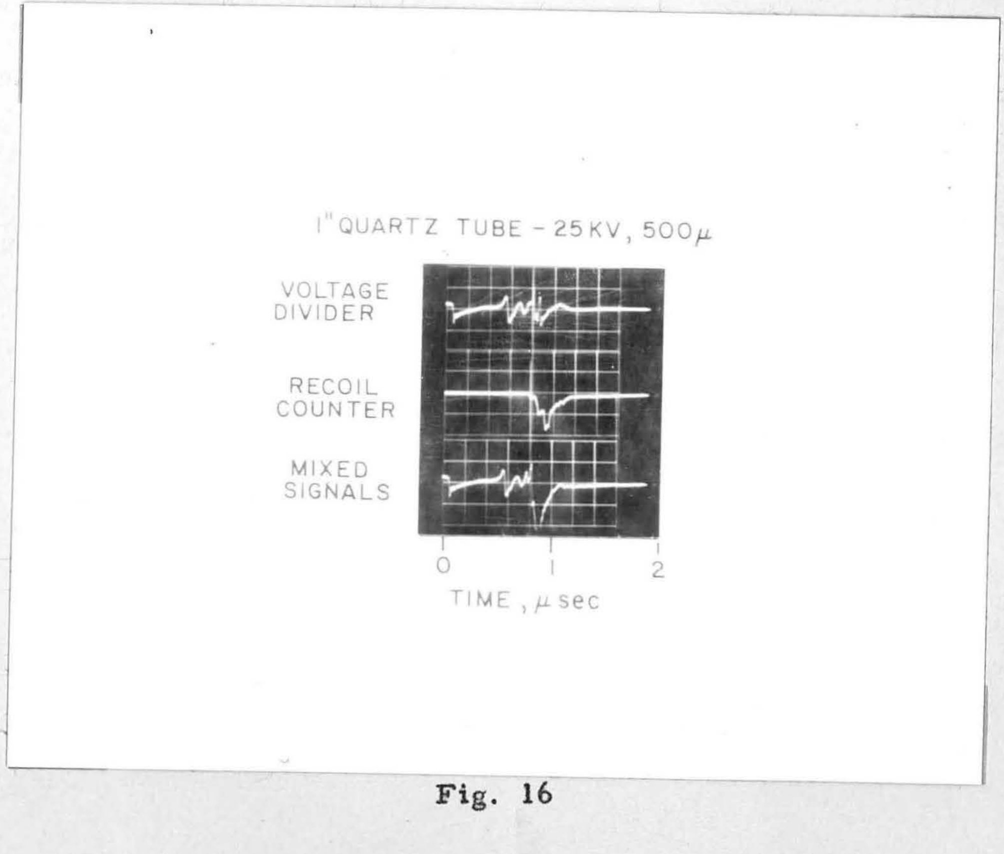

1" QUARTZ TUBE - 25 KV, 500μ
VOLTAGE DIVIDER
RECOIL COUNTER
MIXED SIGNALS
0
1
2
TIME, μsec

Fig. 16

an arc's forming across the shunt (which is exposed to the discharge) we are lowering the shunt resistance. A new electrode is being built with 0.5-in., 1.5-in., 2.75-in. shunts of lower voltage drop.

(4) Study of the initial ionization current and fields trapped within the sheath.

A 2-by-12-in. quartz separator was hung from the top electrode of a 6-by-18-in. pyrex pinch tube, and current inside the separator was measured. The experiment produced strong evidence that the initial ionization current in a pinch tube continues to flow after the sheath is formed, with a decay time of the order of microseconds.

In conclusion, we might mention some plans for the near future. These include more experiments with initial ionization control, including high-frequency ionization, and revival of work with the high-voltage water-condenser energy source for the pinch.

REFERENCE

[1] WASH-289.

DECLASSIFIED

~~SECRET~~

DECLASSIFIED

~~SECRET~~