THE APPLICATION OF HIGH POTENTIALS TO VACUUM-TUBES

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Abstract

A brief progress-report is made on the results so far obtained in the development of vacuum-tubes to which the very high voltages produced by Tesla coils (greater than 10^6 volts) can be applied. One cascade tube has been constructed which withstood repeatedly a voltage of 1,400,000 volts, and others have been used at lower voltages. This method, originally developed by Coolidge, gives promise of being suitable for voltages of several million, and eventually perhaps even higher. No effort has been made so far to use these tubes with a definite and controlled emission, since experience has shown that single-section tubes operated at several hundred kilovolts have approximately the same voltage-limitation with or without hot cathodes. The chief difficulty with very high-voltage tubes is that of preventing the uncontrollable (cold-cathode) emission which limits the voltage which can be applied. An electrodeless tube which withstood 1,000,000 volts is briefly described.

THIS paper is a brief progress-report giving some of our experiences and the results so far obtained in the development of vacuum-tubes to withstand the high voltages so readily produced by means of Tesla coils. Many different designs of tubes have been constructed, with different kinds of electrodes and variations in vacuum technique, and in general our conclusions parallel those of others working on similar problems using other high-voltage sources. It is very difficult to apply more than 300 to 400 kilovolts to a single two-electrode tube, whatever the design or treatment within practical limits. The reason for this is not known exactly at present. The main difficulties are presumably uncontrollable emission and accumulation of charges on the glass walls resulting in punctures and short-circuiting of the voltage source. We have succeeded, however, in applying Tesla voltages of considerable magnitude to vacuum-tubes by two methods, and these results seem interesting enough to merit a brief description.

(1). *The cascade-tube method*—This is essentially the method developed by Coolidge.[1] We have found it possible to use much smaller tubes for the same voltages by immersing them in oil. Figure 1 shows a picture of a 6-section tube used successfully at 850,000 volts. The overall length is 34 inches; the bulbs are of 100-cc size. A tube of similar design with fifteen 300-cc bulbs and having an overall length of 7 feet has gone up repeatedly to 1,400,000 volts. This tube is shown in Figures 2 and 3. Such tubes are at present always used by us on the pumps. The pump system is an ordinary diffusion or Langmuir pump arrangement. The electrodes are copper tubes

[1] W. D. Coolidge, J. Frank. Inst. **202**, 693 (1926).

with rounded ends of as large a radius of curvature as possible, the electrodes being rounded by "spinning" the ends in. We have used Pyrex glass for these tubes for mechanical reasons, although it is quite possible that other glass may prove more advantageous. We have preferred to use each section at a somewhat smaller voltage and to increase the number of

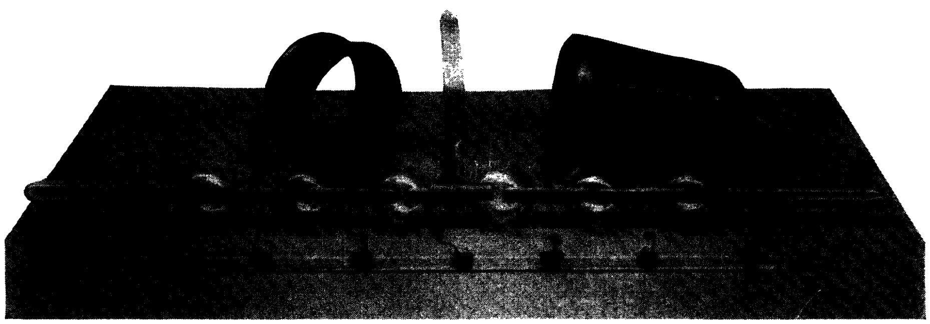

Fig. 1. Six-section tube, with potentiometer and typical shields unmounted.

sections rather than to design each section for operation at the limiting value of 250 or 300 kilovolts, although this no doubt can be done later even with small sections such as we are using. The essential points in the design of tubes are: (*a*) the subdivision of the whole tube into sections; (*b*) the uni-

Fig. 2. Fifteen-section tube.

form distribution of voltage between sections by means of a potentiometer or some other electrical circuit; and (*c*) electrostatic shielding of the sections outside of the vacuum. The type of potentiometer used is shown in Figure 1. The glass tube is filled with a weak solution of salt in water. The concentration of salt is adjusted by trial until the potentiometer connected across the Tesla coil produces a measurable effect on the voltage, for example until it reduces the total voltage by one quarter or somewhat more. The taps of the potentiometer are connected to the successive electrodes of the vacuum-tubes. In operation the potentiometer is put inside the shields.

The type of shield used is also shown in Figures 1, 2, and 3. The 15-section tube, each section of which was 4-3/4 inches long, had shields 3-3/4 inches long, the diameter of each shield being about 8 inches. The spacing between shields was about 1 inch. Experience showed that shielding of bulbs at high potentials is quite necessary. This may apply only to the high-frequency alternating type of potential we are using.

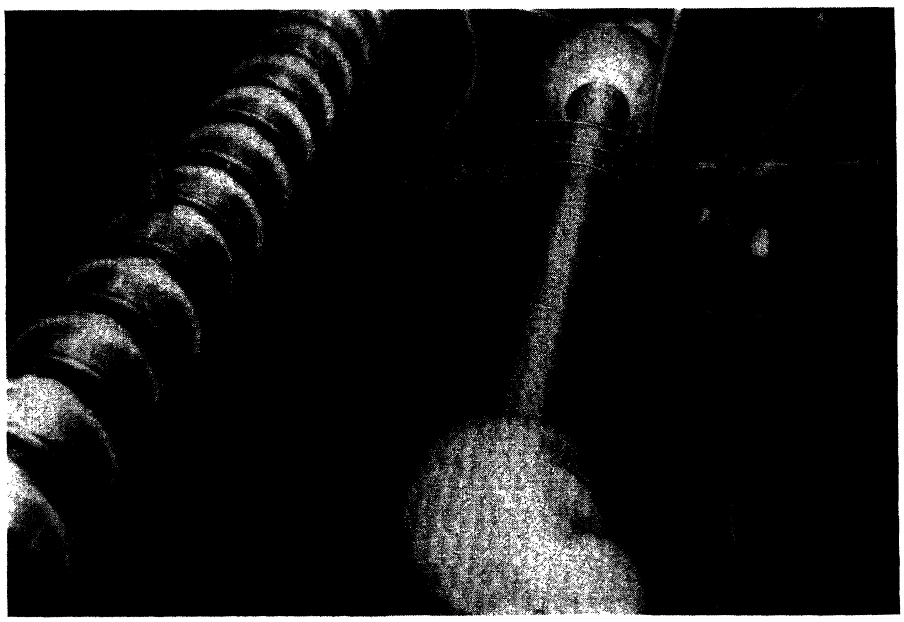

Fig. 3. Fifteen-section tube mounted in steel tank showing shields in position; Tesla coil in place but oil pumped out.

As is seen in Figure 1 the connections to the electrodes were made through waxed joints. There was thus no question of an extremely high vacuum since the tube as a whole could not be baked. The electrodes themselves (copper) were prebaked at 950°C in a quartz-tube furnace. The tube was also torched with a gas flame while evacuated, before the electrodes were put in. Carbon-dioxide snow in alcohol was used on the trap for keeping down the pressure of Hg and other condensible vapors. No refrigerant was used during the first half-hour of pumping, in order to pump out most of the water-vapor. Liquid air on the trap obviously might be quite dangerous in case of an accident, since the tubes are tested under oil. As indicative of the rather low degree of vacuum required it may be of interest to mention that the 15-section tube withstood 1,000,000 volts without trouble only 4 hours after it was assembled and the pumps started. This was without torching any of the glass parts.

An important point about bringing up a tube to a high voltage is "breaking in" as in the case of x-ray tubes on direct current or low-frequency alternating current. When a potential is first applied the tube may flash at one-half of the potential which it stands without puncture after it is broken in. Our procedure is to bring the potential up cautiously until the tube flashes. Then the potential is lowered until the flashing weakens appreciably. After a few minutes running or less the flashing disappears. The potential is brought up until the tube flashes again and the procedure is repeated. In cases where one of a set of bulbs shows bad flashing it is sometimes helpful to break this section in by itself. There is of course an approximate limit which a given size of bulb of a given design will not exceed. The potential which can be applied to the whole tube is however rather accurately equal to the potentials which may be applied to the bulbs separately. Thus the bulbs act independently. The "breaking in" procedure may at times be carried out safely by letting the tube flash and allowing it to rest for a minute or two. Then the potential is applied again. The flash is often weaker or absent. It seems that it is important to pump off the gases evolved during a flash. The "breaking in" of a tube is somewhat similar to the "breaking in"of oil described in the preceding article. The "breaking in" lasts, that is, if a tube is broken in one day it can be broken in to the same voltage on the next day in a much shorter time. At times no "breaking in" the next day is required. In all of these experiments we use the intermittent voltage-excitation by means of a stationary primary gap and direct current on the primary condenser described in the preceding article. It may be that the same tubes would be subjected to more danger if used on other and more continuous sources of potential.

It will be noticed that the increase in the potential applied to the 15-section tube over that used on the earlier 6-section one was not proportional to the number of sections and was especially out of proportion to the total lengths. It might be supposed that the use of tubes with many sections is disadvantageous. No such limitation was responsible for the insufficiently high voltage applied to the larger tube. One of the shields which was insufficiently well supported, fell on the tube and caused a puncture at the point of contact with the glass during the "breaking in" process. The flashing at 1,400,000 volts was not due to lack of additivity in the action of the bulbs, because the bulbs when tried separately flashed at about 100,000 volts per bulb. This relatively bad performance of the bulbs was in all probability due to partial contamination of the electrodes with mercury which occurred during an accident to the tube. The amount of work involved in taking the electrodes out, baking them, and putting them in again being considerable, the tube was repaired without removing the electrodes. Since the electrodes in the 15-section tube were larger and more nicely rounded than in the 6-section tube and since the bulbs in it were also larger there is every reason to expect at least one-sixth of 850,000 volts per section when care is taken to have uncontaminated electrodes. It must also be mentioned that one of the 15 sections was not used because of a defect in the potentiometer at that section. The additivity of potentials which may be applied to the bulbs separately when they are connected in series seems thus to be demonstrated. We expect therefore that a 2,000-kilovolt tube can be constructed without serious difficulty.

So far we have tried hot cathodes in single-section rather than cascade tubes. The puncture-voltage was independent of whether a hot cathode was used or not. The evidence is that its use will not make the operation on the cascade principle more difficult.

(2) *Electrodeless tubes*—These have been mentioned by us in a previous publication.[2] Under proper conditions a spherical Pyrex bulb immersed in oil between electrodes does not puncture when a million volts is applied to the electrodes. The arrangement is shown in Figure 4. The exact conditions for successful operation of such bulbs are still not certain. The evidence

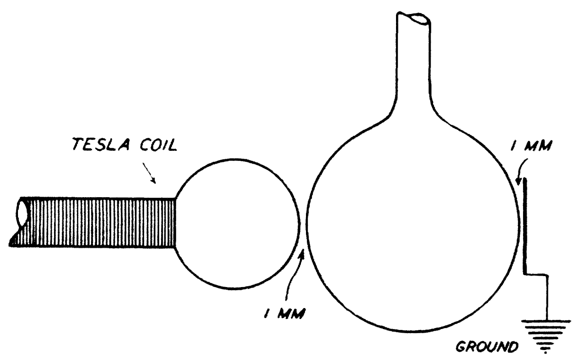

Fig. 4. Diagrammatic sketch showing the arrangement for electrodeless tube.

seems to be however that a partially electrically conducting-layer on the inside surface of the glass, in our case due to carbonized oil, is essential. The fluorescence patches of long duration observed with this type of bulb are quite similar to those occurring with the cascade-bulbs.

(3) *Miscellaneous experience*—Long tubes, with one electrode at each end put inside the Tesla, puncture readily. The high-frequency field produced by the Tesla is thus insufficient to prevent accumulation of charges inside the tube.

Sealed off commercial Coolidge tubes at times stand a higher Tesla voltage than would be expected from their behavior on direct current. This however is not always true. It was impossible in our experience to exceed 400 kilovolts without bad flashing. One 220-kilovolt deep therapy tube was punctured at 400 kilovolts.

An extraordinarily good vacuum is not essential in securing good operation of single-section tubes up to say 300,000 volts. Extreme precautions

[2] G. Breit and M. A. Tuve, Nature **121**, 535 (1928).

with regard to vacuum technique do not suffice in our experience to bring about anything but very erratic improvements beyond this figure.

One quite definite type of failure is that shown by "straight" tubes, whether single or cascade, made by enclosing the electrodes in ordinary drawn Pyrex tubing of a diameter not much larger than that of the electrodes themselves, instead of in bulbs. Such a rigid design of tube would be mechanically very desirable, but 10-section and 20-section tubes made in this way have failed well under 500,000 volts, the glass wall shattering inward from longitudinal striae or bubbles in the glass without puncturing through to the outside. Violent flashing then limits the voltage which can be applied. The striae are usually invisible before the shattering takes place.

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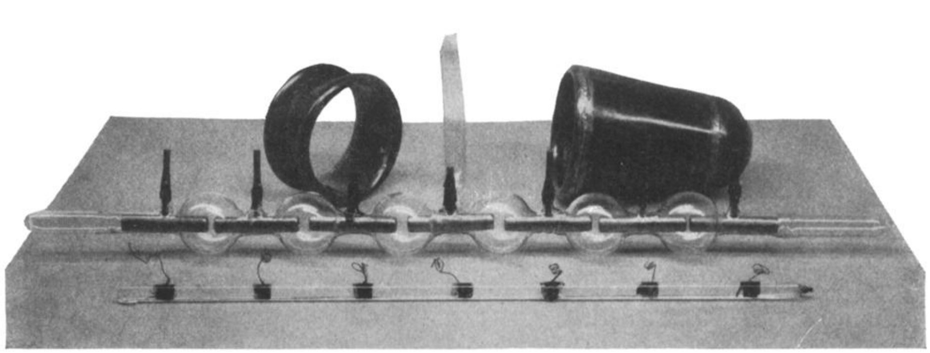

Fig. 1. Six-section tube, with potentiometer and typical shields unmounted.

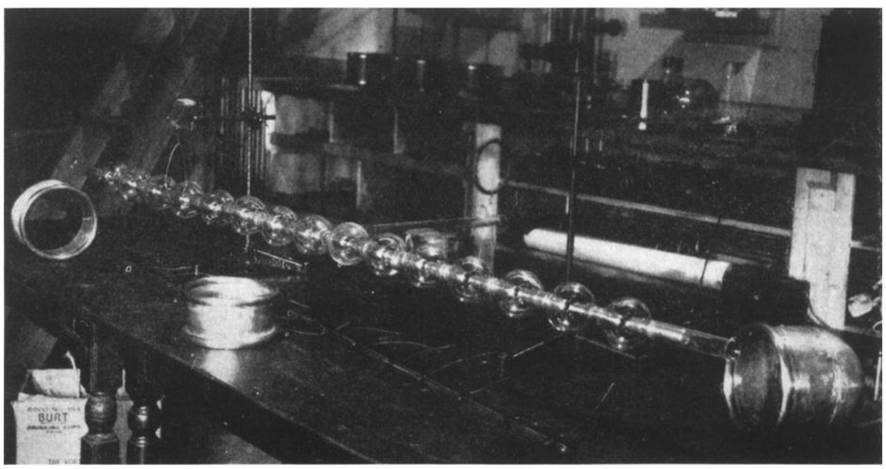

Fig. 2. Fifteen-section tube.

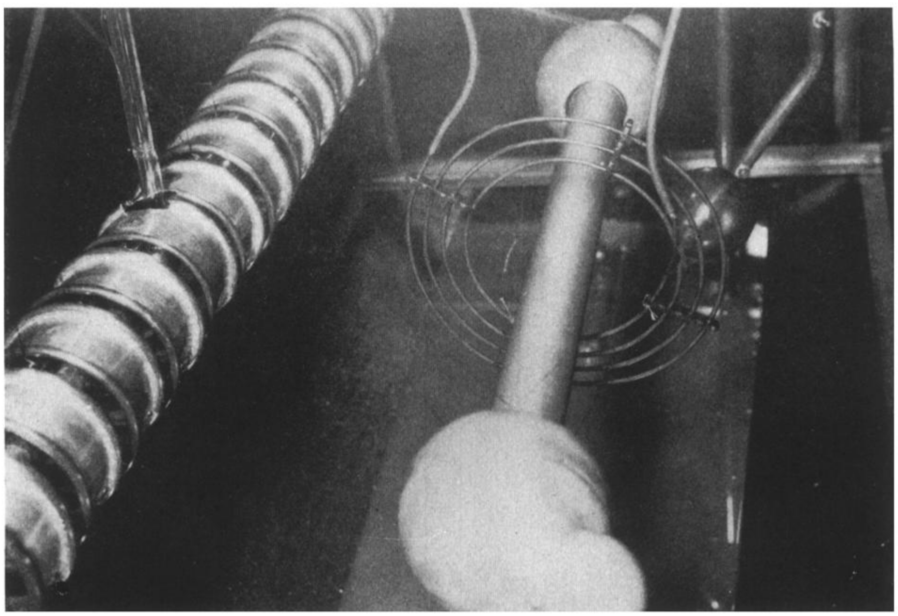

Fig. 3. Fifteen-section tube mounted in steel tank showing shields in position; Tesla coil in place but oil pumped out.