DESIGN AND CONSTRUCTION OF A CONSTANT POTENTIAL X-RAY VOLTAGE SUPPLY

by

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A THESIS submitted to OREGON STATE COLLEGE

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

June 1948
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DESIGN AND CONSTRUCTION OF A CONSTANT POTENTIAL X-RAY VOLTAGE SUPPLY

INTRODUCTION

Since the discovery of x-rays by Röntgen in 1895, their applications have been extended to a great many fields. Because of their ability to penetrate matter, and some substances more readily than others, they were put to immediate use in the medical field. Today x-ray equipment is a necessary part of every physician's office. Industry has also developed elaborate x-ray techniques to examine castings and the internal structure of metals that are otherwise inaccessible. Simultaneously with the developments mentioned, their nature was studied and applications of these short electromagnetic waves were made to problems of the physicist. For studying the fundamental properties of matter their utilization has opened a new realm of investigation.

When x-ray tubes were first studied they were energized by induction coils or static machines that happened to be accessible. As they became larger, more and more attention had to be paid to the source of the electrical energy. This led to the development of numerous special devices and circuits of which several will be reviewed. The problem of this thesis is the construction and testing of a supply circuit from
apparatus available in the laboratory that will produce a controllable high voltage having only a minute ripple. This requirement is not necessary for ordinary radiography but becomes highly desirable for x-ray diffraction and also for electron diffraction experiments.
HISTORY OF X-RAYS

Late in 1895 some experiments on the properties of cathode rays were being conducted at the University of Würzburg in Germany by Professor W. C. Röntgen. Since he was studying the fluorescence caused by the cathode rays, he was working in a dark room and had to cover his cathode ray tube with a black cardboard box which prevented visible light and ultraviolet radiation from escaping. In spite of this, he observed that his fluorescent screen glowed brilliantly when brought near the covered tube. Investigating this phenomenon, he concluded that it was caused by emission of some unknown type of invisible radiation from the cathode ray tube. In his first published paper describing the new rays, which he called x-rays, he mentioned their penetrating ability as well as their ability to excite fluorescence in suitable substances.

Many other investigators immediately began experiments with these new penetrating rays but very little progress as to their real nature was made until the discovery of x-ray crystal diffraction by M. von Laue in 1912 at Munich. Earlier experimenters had tried to produce interference and diffraction effects with x-rays but except for Haga and Wind had
met with little success and even their measurements were not accepted until after Laue's work (1, p. 20).

Assuming that x-rays consist of waves having a length of the order of $10^{-9}$ centimeters, it occurred to Laue that crystals, having a space lattice structure with an interatomic distance of the order of $10^{-8}$ centimeters, might act as a diffraction grating for x-rays. W. Friedrich and P. Knipping, two doctoral candidates, set up suitable apparatus and soon discovered that diffraction patterns of the type predicted by Laue were actually produced by crystals of copper sulphate, zinc blende, rock salt, and galena. It is of course evident that this method can be used not only to measure the wavelength of x-rays, but also to determine intermolecular distances providing that one wavelength or one such distance can be determined by some independent means.

The next important step was the invention of the Coolidge tube by Dr. W. D. Coolidge of the General Electric Research Laboratory in 1913. From 1895 to 1913 all x-ray tubes were of the so-called "gas-filled" type. These were suitable for certain types of work at less than 50,000 volts and are still often used in diffraction work, but their manipulation was difficult as the number of electrons emitted from the cold
cathode was not independent of the voltage applied to the tube. By introducing a heated tungsten filament to serve as a source of electrons, Coolidge made the number of electrons controllable by the filament current and the speed of the electrons by the voltage applied to the tube. With the tube exhausted to the highest obtainable vacuum the output of a Coolidge tube can be accurately controlled and results duplicated (2, p. 371-373).

Another important discovery was also made in 1913 by H. G. J. Moseley of Oxford. He found that a portion of the x-rays radiated from the target of an x-ray tube has a wavelength characteristic of and dependent upon the atomic number of the target material. This discovery led to the establishment of a satisfactory theory of the origin of these characteristic x-ray spectra and also helped theoretical physicists to arrive at a fundamentally correct theory of the structure of the atom.

The final discovery that will be mentioned is that of A. H. Compton whose theoretical explanation of the scattering process (1, p. 204-207) has become one of the basic tenets of modern physics.
PRODUCTION OF HIGH VOLTAGES

In the preceding historical sketches it has been inferred that the x-rays are produced at the target of the tube where it intercepts the cathode rays or stream of electrons. These electrons are, of course, accelerated toward the target by a difference of potential maintained by an external circuit. The circuits are those ordinarily used in the production of high voltages. The simplest circuit is one in which the secondary of a high voltage transformer is connected directly across the x-ray tube. If this is used for diffraction work the tube is usually operated with the anode at ground potential so that any auxiliary apparatus can also be grounded. The tube acts as its own rectifier so that during the a.c. cycle there is current only when the anode is positive.

The advantages of the circuit are its simplicity, compactness, and low cost. One of its disadvantages is that, as in all half wave rectified circuits, the tube is idle during the inverse half of each cycle.

Another type of circuit commonly used is the Villard circuit shown in Figure 1. Using two kenotrons and two condensers it is a voltage-doubling circuit in which the voltage applied to the x-ray tube has
Figure 1. Villard circuit.
a peak value approximately twice the maximum supplied by the transformer. In this type of circuit each kenotron and also each condenser must withstand an inverse voltage equal to the full transformer voltage. This circuit accomplishes several desirable objectives. Very high tube voltages can be obtained with a transformer of moderately high voltage because of the voltage-doubling feature. The tube is subjected to practically no inverse voltage thus increasing the tube life. The average forward voltage is not very high, however, as it drops to zero once each cycle.

The action in the circuit during the cycle may be shown by following the diagram in Figure 1. At the start of the a.c. cycle points A and B are at the same potential. One quarter cycle later when A and the lower plate of C₁ have reached a potential with respect to ground of \(-\frac{V}{2}\), B and the lower plate of C₂ will have reached a potential of \(\frac{V}{2}\). During this quarter cycle, electrons will flow off the upper plate of C₁ through the kenotron K₁ to ground and also from ground through the kenotron K₂ to the upper plate of C₂. During the second quarter cycle, the lower plates of both condensers return to ground potential but the upper plate of C₁ cannot regain its lost electrons through K₁ hence will remain at a potential
of $+V/2$. Likewise the upper plate of $C_2$ cannot get rid of its excess electrons through $K_2$ and will thus remain at $-V/2$. During the third quarter cycle, $A$ and the lower plate of $C_1$ reach a potential of $-V/2$ while $B$ and the lower plate of $C_2$ reach a potential of $-V/2$. The electrons cannot pass through $K_1$ and $K_2$ in the inverse direction, so the potential of the upper plate of $C_1$ is still $+V/2$ with respect to the lower plate or $+V$ with respect to ground, and the upper plate of $C_2$ is $-V/2$ with respect to the lower plate or $-V$ with respect to ground. The difference in potential between the upper plate of $C_1$ and the upper plate of $C_2$, which is the potential across the x-ray tube, thus reaches a value approximately $2V$ or twice the full transformer voltage. During the fourth quarter cycle the potentials of the lower condenser plates return to zero and the potential difference across the tube drops to $V$. During the next quarter cycle the potential of $A$ and the lower plate of $C_1$ drops to $-V/2$ while $B$ and the lower plate of $C_2$ reach $+V/2$. The upper plates are then at ground potential again and there is no voltage applied across the x-ray tube.

Perhaps the most popular circuit is the Greinacher circuit. This comprises an arrangement of condensers and kenotrons that produce very high voltages (3, p. 197).
Figure 2. Greinacher circuit.
With two condensers and two kenotrons arranged as shown in Figure 2, it acts as a voltage-doubling circuit and also furnishes a potential across the tube that has only a small ripple at twice the frequency of the applied voltage. The transformer must be of the end-grounded type or else it must be set on an insulating stand and the primary fed from an isolating transformer. The two condensers need to withstand only the transformer voltage equal to the full tube voltage or twice the transformer voltage.

The amount of ripple may be computed if the capacitance of the condensers is known. When one of the condensers is fully charged, its charge in coulombs will be \( Q = CV \) where \( C \) is the capacitance in farads and \( V \) is the peak transformer voltage. Both condensers will experience a discharge current and lose a quantity of electricity \( q = \) It where \( I \) is the current in the x-ray tube and \( t \) is the time interval for 1/2 cycle. The fraction of the total charge lost by each condenser, and thus the voltage drop, is \( q/Q \). The percent of the voltage drop is this value multiplied by one hundred (4, p. 134-135).

By referring to Figure 2 the action in this circuit may be followed. At the start of the a.c. cycle the point A is at ground potential. During the first
quarter of the cycle A is raised to a potential of $-V$. The lower plate of $C_1$ remains at ground potential and electrons will flow through the kenotron, $K_1$, leaving the upper plate at a potential $+V$. During the second quarter cycle the potential of the point A returns to zero but the electrons that left the upper plate of $C_1$ cannot return through $K_1$ so it remains at the potential $+V$. During the third quarter cycle A reaches a potential $-V$ and electrons can flow through $K_2$ so that the upper plate of $C_2$ reaches a potential $-V$. The upper plates of both condensers are across the x-ray tube so its difference in potential is thus $2V$. During the fourth quarter cycle the point A returns to zero and the condensers must supply the x-ray tube current. The voltage will thus drop until condenser $C_1$ is raised to potential $+V$ again during the first quarter of the following cycle. During the third quarter of this second cycle, $C_2$ will again reach the potential $-V$. This accounts for a ripple voltage having two pulses each cycle. The time during which the condensers must furnish the tube current, and hence the voltage drop, may be reduced by using the higher frequency. The rate at which the tube voltage drops between the peaks of the cycle is directly proportional to the x-ray tube current and inversely proportional to the capacitance
Figure 3. Gratz full-wave circuit.
of the condensers.

The bridge type of rectifying circuit, sometimes called a Gratz circuit, is shown in Figure 3. It requires four kenotrons and by using two condensers, each withstanding half the tube voltage, the pulses in ordinary full-wave rectification may be smoothed out to obtain a potential across the tube with only a slight ripple. Each kenotron must be able to withstand an inverse voltage equal to the full x-ray tube voltage. The transformer must generate the full tube voltage since this is not a doubling circuit.

The last circuit that will be described is a full-wave rectifying circuit requiring two kenotrons as shown in Figure 4. It is well adapted for x-ray diffraction (6, p. 375-383) and especially for electron diffraction work by the addition of a condenser as shown. Such work as a rule does not require potentials above 50 kilovolts. It is advantageous to have the tube grounded at the positive end so that all the apparatus except the cathode will be grounded. The potential supplied to the x-ray tube or the electron gun of the electron diffraction apparatus is only half the transformer voltage. This circuit might therefore be called a voltage halving circuit. The kenotrons must each withstand the full transformer voltage, which
Figure 4. Two kenotron full-wave circuit.
is twice the tube voltage, but the condenser must withstand only the tube voltage. The action of this circuit may easily be followed. The lower plate of the condenser and the center tap of the transformer secondary are grounded. During the half of the cycle in which A is negative, the kenotron \( K_1 \) will conduct and the upper plate of the condenser will be charged to a potential \(-V/2\) where \( V \) is the full transformer voltage. During the other half of the cycle, B will become negative and \( K_2 \) will conduct so that the condenser will again be charged to a potential \(-V/2\). The percent ripple may be calculated as before.

There are many other circuits that might be used (5, p. 80-85) and each has some features to commend it.

In this thesis the circuits shown in Figure 2 and Figure 4 were employed and their output wave forms analyzed.
DESCRIPTION OF THE APPARATUS

HIGH VOLTAGE TRANSFORMER. The available high voltage transformer has a centergrounded secondary and produces 100,000 volts. Since voltage-doubling circuits require an endgrounded secondary, only half the secondary of the transformer was used.

RECTIFIER TUBES. The two tubes used in the rectifier circuits are General Electric KR-6 kenotrons built to operate at a maximum of 140 kilovolts peak, when oil immersed, or 50 kilovolts in air. The filament current is 14 amperes at 11 volts, and the rectified current is rated at one ampere.

FILAMENT TRANSFORMERS. The filament transformers for the kenotrons were specially wound and with 110 volts input give 11 volts on the secondary.

CONDENSERS. The smoothing condensers are of two different types. Four were constructed using insulating plates of ordinary glass and conducting plates of aluminum foil shellacked to one side of each plate. The foil was trimmed back from the edges of the glass 1.5 cm. on the sides and bottom and 3 cm. on the top where contacts were brought out to leads connecting alternate plates. The capacitance in microfarads of each of these may be calculated from the formula
\[ C = \frac{N K_0 A}{36 \pi d} 10^5 \] where \( N \) is one less than the number of conducting plates, \( K_0 \) the permittivity of the glass, \( A \) the area in square centimeters of each of the conducting plates, and \( d \) the thickness of each glass plate in centimeters. For the material used \( N = 29 \), \( K_0 = 7 \), \( A = 280 \text{ cm.}^2 \), and \( d = 0.34 \text{ cm.} \). Thus \( C = 0.0146 \text{ microfarads} \). Each of the four condensers consisted of 29 plates mounted in glass containers and immersed in transil oil to prevent corona losses and breakdown around the edges of the glass plates. Each condenser was found to withstand voltages up to 30 kilovolts.

Two other condensers were made with larger plates on "double thick" glass; with \( N = 18 \), \( K_0 = 7 \), \( A = 470 \text{ cm.}^2 \), and \( d = 0.46 \text{ cm.} \), \( C \) was computed to be 0.011 microfarads. These values of capacitance were checked on a General Radio bridge.

**POWER SOURCES.** A motor generator set operating on 110 volts d.c. was used to supply 500 cycle a.c. to the primary of the high voltage transformer. The voltage could be varied from 0 to 140 volts by means of a rheostat in series with the generator field.

A variac that replaced the 500 cycle generator of the original circuit served to introduce 60 cycle power variable from 0 to 130 volts.
AUXILIARY APPARATUS. To check the circuits under actual conditions, the output was applied to a Coolidge tube. A milliammeter with a full scale deflection of 20 milliamperes was used to measure the tube current. By connecting the primary of the x-ray tube filament transformer through a small 5 ampere variac the tube current could be accurately controlled. A microammeter in series with a 100 megohm resistor across the output terminals of the high voltage was used to measure the voltage. A calibrated spark gap, consisting of two spheres 12.5 centimeters in diameter, connected through high resistance and across the high voltage terminals made it possible to check the voltage measurements as read on the microammeter. The oscilloscope used to show the wave forms is a type 241 made by the Allen B. DuMont Laboratories, Inc. The camera used to photograph the wave forms on the oscilloscope screen was a 35 millimeter French "Sept" with an adapted f-1.9 lens.
OPERATION AND RESULTS

The Greinacher circuit and the full-wave two kenotron circuit shown in Figure 2 and Figure 4 respectively were used and their output wave form checked under various operating conditions. Figure 5 is a photograph of the experimental arrangement of the apparatus with the omission of the 500 cycle motor generator set and the variac used to supply 60 cycle power. Figure 7 shows the camera set up to take photographs of the oscilloscope screen during operation. Figure 6 is a close up of the x-ray tube, showing the 100 megohm resistor, the x-ray milliammeter and the microammeter used to measure the voltage. The resistor is connected to the input terminals of the oscilloscope by a shielded cable as shown in Figures 8, 9, 10, and 11.

Table I gives the calculated percent ripple indicated under ideal operating conditions: capacitors have no resistance and absence of corona losses. The series of 38 oscilloscope wave forms are reproductions of the photographs taken and are numbered serially for reference.

Oscilloscope patterns numbered 1 to 16 refer to the Greinacher circuit. The high voltage was reduced
TABLE I

Calculated Percent Ripple at Ideal Operating Conditions

Greinacher Circuit \( (C_1 = C_2 = 0.018 \text{ uf}) \)

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Ripple voltage</th>
<th>Ripple voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,000 volts</td>
<td>5 mil.</td>
<td>11.5%</td>
</tr>
<tr>
<td>20,000 volts</td>
<td>10 mil.</td>
<td>23.0%</td>
</tr>
<tr>
<td>30,000 volts</td>
<td>5 mil.</td>
<td>7.7%</td>
</tr>
<tr>
<td>30,000 volts</td>
<td>10 mil.</td>
<td>15.4%</td>
</tr>
</tbody>
</table>

60 cycles

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Ripple voltage</th>
<th>Ripple voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,000 volts</td>
<td>5 mil.</td>
<td>1.39%</td>
</tr>
<tr>
<td>20,000 volts</td>
<td>10 mil.</td>
<td>2.78%</td>
</tr>
<tr>
<td>30,000 volts</td>
<td>5 mil.</td>
<td>0.925%</td>
</tr>
<tr>
<td>30,000 volts</td>
<td>10 mil.</td>
<td>1.85%</td>
</tr>
</tbody>
</table>

500 cycles

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Ripple voltage</th>
<th>Ripple voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,000 volts</td>
<td>5 mil.</td>
<td>5.95%</td>
</tr>
<tr>
<td>20,000 volts</td>
<td>10 mil.</td>
<td>11.8%</td>
</tr>
<tr>
<td>20,000 volts</td>
<td>20 mil.</td>
<td>23.6%</td>
</tr>
<tr>
<td>30,000 volts</td>
<td>5 mil.</td>
<td>3.86%</td>
</tr>
<tr>
<td>30,000 volts</td>
<td>10 mil.</td>
<td>7.72%</td>
</tr>
</tbody>
</table>

Full-wave Circuit \( (C = 0.036 \text{ uf}) \)

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Ripple voltage</th>
<th>Ripple voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,000 volts</td>
<td>5 mil.</td>
<td>0.69%</td>
</tr>
<tr>
<td>20,000 volts</td>
<td>10 mil.</td>
<td>1.38%</td>
</tr>
<tr>
<td>20,000 volts</td>
<td>20 mil.</td>
<td>2.76%</td>
</tr>
<tr>
<td>30,000 volts</td>
<td>5 mil.</td>
<td>0.462%</td>
</tr>
<tr>
<td>30,000 volts</td>
<td>10 mil.</td>
<td>0.924%</td>
</tr>
</tbody>
</table>
Figure 5. Experimental arrangement for Greinacher circuit.

Figure 6. X-ray tube, resistor, milliammeter and microammeter.
Figure 7. Camera and oscilloscope.
before applying it to the oscilloscope in the usual manner as shown in Figure 8. Patterns 1 to 8 show the base line for zero applied voltage and the high

![Oscilloscope connections diagram](image)

Figure 8. Oscilloscope connections.

voltage waveform. The distance from the base line to the peak of the applied voltage represents the voltage stated on each diagram. The distance from the maximum to the minimum of the high voltage represents the voltage ripple. Patterns 1 to 4 were obtained with a 60 cycle input. These show very poor regulation with percentage ripples of 40%, 73%, 31.8%, and 54.5% respectively. Using a 500 cycle input the ripple is reduced as shown in patterns 5, 6, 7, and 8. The percent ripple is 2.6%, 3.67%, 1.45%, and 1.89% respectively.

To obtain the patterns 9 to 16 inclusive, the
high voltage was reduced as shown in Figure 9 before being applied to the oscilloscope terminals. These patterns show in detail the wave form of the ripple voltage under the operating conditions stated.

Patterns 17 to 38 inclusive were taken with the two kenotron full-wave circuit. To obtain patterns 17 to 26 the voltage was applied to the oscilloscope as shown in Figure 10. The oscilloscope pattern shows zero voltage and the wave form of the high voltage. As before, the distance from the base line to the peak of the wave form represents the high voltage and that from maximum to minimum the voltage ripple.

Patterns 17 to 21 were taken with 60 cycle input. At the voltage and tube current stated the percent ripple was respectively 6.20%, 10.4%, 17.4%, 3.92%, and
7.86%. Using 500 cycle input, shown in patterns 22 to 26 the corresponding figures are 1.03%, 1.68%, 2.66%, 0.73%, and 1.24% respectively.

Figure 10. Oscilloscope connections.

Patterns 27 to 31 inclusive were obtained by applying the voltage to the oscilloscope as shown in Figure 11. These show the details of the wave form with 60 cycle input voltage. Pattern 32 shows the wave form produced with 4.00 volts applied to the terminals of the oscilloscope directly, care being taken not to change the gain controls as set in taking patterns 22 to 31. Comparison of the amplitudes gives an indication of the voltage previously applied although exact calculations cannot be made since the amplification of the oscilloscope is not linear.

Patterns 33 to 37 show the wave form obtained with
500 cycle input. The voltage was applied to the oscilloscope as shown in Figure 11. Pattern 38 shows the waveform when the voltage was 1.47 and 500 cycles.

The waveforms obtained and the computations made on the voltage ripple clearly show the advantages of 500 cycle over 60 cycle input and of the full-wave two kenotron circuit over the Greinacher voltage-doubling circuit. The condensers that must be in series in the Greinacher circuit can be operated in parallel in the full-wave circuit and thus increase the capacitance. Where voltages of less than 50,000 are required the fact that the voltage obtained from the full-wave two kenotron circuit is only half the transformer voltage is not a disadvantage.
20,000 VOLTS
5 MILLIAMPERES
60 CYCLES

30,000 VOLTS
5 MILLIAMPERES
60 CYCLES

GREINACHER CIRCUIT
20,000 VOLTS
5 MILLIAMPERES
500 CYCLES

30,000 VOLTS
5 MILLIAMPERES
500 CYCLES

GREINACHER CIRCUIT
GREINACHER CIRCUIT
GREINACHER CIRCUIT
20,000 VOLTS
5 MILLIAMPERES
60 CYCLES

20,000 VOLTS
10 MILLIAMPERES
60 CYCLES

20,000 VOLTS
20 MILLIAMPERES
60 CYCLES

30,000 VOLTS
5 MILLIAMPERES
60 CYCLES

FULL-WAVE TWO KENOTRON CIRCUIT
FULL-WAVE TWO KENOTRON CIRCUIT
FULL-WAVE TWO KENOTRON CIRCUIT

30,000 VOLTS
5 MILLIAMPERES
500 CYCLES

30,000 VOLTS
10 MILLIAMPERES
500 CYCLES
20,000 Volts
5 Milliamperes
60 Cycles

20,000 Volts
10 Milliamperes
60 Cycles

20,000 Volts
20 Milliamperes
60 Cycles

30,000 Volts
5 Milliamperes
60 Cycles

FULL-WAVE TWO KENOTRON CIRCUIT
30,000 VOLTS
10 MILLIAMPERES
60 CYCLES

60 CYCLES

20,000 VOLTS
5 MILLIAMPERES
500 CYCLES

20,000 VOLTS
10 MILLIAMPERES
500 CYCLES

FULL-WAVE TWO KENOTRON CIRCUIT
20,000 VOLTS
20 MILLIAMPERES
500 CYCLES

30,000 VOLTS
5 MILLIAMPERES
500 CYCLES

30,000 VOLTS
10 MILLIAMPERES
500 CYCLES

FULL-WAVE TWO KENOTRON CIRCUIT
BIBLIOGRAPHY


