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TWIN-TANK ACCELERATOR FOR HIGH-VOLTAGE ELECTRON MICROSCOPY (HVEM)

Günter Reinhold and Roger Gleyvod Accelerator Department, Emile Haefely & Co Ltd, 4000 Basel 28 Switzerland

#### Summary

HVEM has become a useful method of research in metallurgy and biology. It was necessary to develop special electron accelerators for the supply of these high-voltage microscopes. In view of ac interference problems with air-insulated accelerators, a commercial 1 MV twin-tank accelerator was introduced in 1967. The voltage in this basic model was extended to 1.5 MV and stability improved from  $\pm 1 \ge 10^{-5}$  to  $\pm 1 \ge 10^{-6}$ . The future requirements of the electron microscopists, which are directed towards even higher accelerating voltages and greater stability, can also be met by the principles of the symmetrical cascade generator and twintank accelerator.

### Definition

Commercial electron microscopes operate nominally at accelerating voltages of 100 kV; more recent models have achieved voltages up to 200 kV. It has been accepted verbiage internationally -- without formal agreement -to apply the term "high-voltage electron microscopes" to apparatus operating at accelerating voltages in the megavolt range and above 500 kV.

## Development of High-Voltage Electron Microscopes

In the evolution of high-voltage electron microscopy, which has already spanned four decades, the development and breakthrough in high-voltage microscopy was achieved in the last ten years. The first high-voltage electron microscope, which operated at a maximum accelerating voltage of 1.5 MV, was designed and built by G. Dupouy and his team about 1960 at the Laboratoire d'Optique Electronique in Toulouse, France. This constituted a breakthrough in high-voltage microscopy and triggered rapid developments in the field. During the development phase, single units and laboratory models were built; e.g. the 750 keV microscope by V. E. Cosslett at the Cavendish Laboratory, Cambridge, England, and the 1 MeV electron microscope for the Research Center, U. S. Steel Corporation, Monroeville, Pa., USA, by RCA. Then, the first commercial models were made available by European and Japanese manufacturers with rated voltages of between 650 kV and 1.2 MV. In 1969, electron microscopes were commissioned in both France and Japan, in the hope of reaching a maximum operating voltage of 3 MV. A 10 MV microscope, which will be supplied by a linear accelerator, is presently being built in Japan.

# Advantages of High-Voltage Microscopy

Increase in accelerating voltage, theoretically, makes it possible to improve the point resolution. In practice, resolution values will be approximately 10 Å for standard electron microscopes, approximately 5 Å for 1 MV, high-voltage microscopes, and below 1 A for 3 MV installations. Higher energy of the electron beam allows the penetration of specimens of greater thickness and higher density. This advantage is of importance in metallurgy (particularly in crystallography), biology, and medical research (i.e., chromosome research in genetics). Tests have also been conducted to isolate live viruses (which cannot be observed under vacuum in ordinary electron microscopes) under normal conditions of life in microchambers, the walls of which can be penetrated without difficulty by the energy-rich electrons. In the USA, highvoltage microscopes have been invaluable in the examination of lunar rock.

### The Physical Difference Between Standard and High-Voltage Microscopes

High-voltage microscopes do not show any major differences in construction when physically compared to standard productions. However, a considerable difference exists in the electron-beam system. In the high-voltage microscope, the electron gun must be replaced by a complete electron accelerator, which gives the required high energy to the electrons.

# Requirements of the Electron Accelerator

Four parameters are to be considered in determining the quality of an electron microscope:

- 1. Stability of the accelerating voltage.
- Mechanical precision and tolerances of the electomagnetic lenses.
- 3. Stability of the lens supply currents.
- Absence of movement and vibration, selfinduced or transmitted from the outside.

Because of the need for freedom from vibration, the high-voltage Van de Graaff generator is eliminated. The linear-accelerator type is not suitable because of the aforementioned requirements of high-voltage stability. The cascade generator is recommended, particularly in the symmetrical circuit. For this reason, almost all highvoltage electron microscope's are supplied today by simple or symmetrical cascade recti-

fiers. In order to approach the theoretical value of the resolving power, the stability of the accelerating voltage for recording the micrograph must lie between  $1 \times 10^{-6}$  and  $1 \times 10^{-5}$ , including the ripple voltage, during the exposure time. The requirements that the accelerating voltage must be variable between 10 % and 100 % of the rated voltage poses another difficulty; namely, that the sensitivity of the regulating equipment must be 10 times greater than at the rated voltage. The beam current employed is in the range of microamperes. In fact, only a millionth part is used in the microscope for production of the image, i.e., electron currents of  $10^{-11}$  A up to  $10^{-12}$  A.

### The Air-Insulated Electron Accelerator

The first electron accelerators for highvoltage microscopy were of open-design construction; i.e., the air-insulated type. Fig. 1 shows a 1 MeV accelerator which consists of a simple cascade rectifier with an additional filter column (figure - right) connected to the actual accelerator structure by means of a high-ohmic damping and filter resistor.



Fig. 1: 1 MeV Electron Accelerator of the RCA Electron Microscope at Research Center of U. S. Steel Corporation, Monroeville, Pa., USA

# Interference Problems in Open Accelerators

Practical experience with air-insulated installations has shown that ac voltages superimposed on dc voltages at various points on the high-voltage circuit and also on the accelerator tube are greater than was expected due to the filter factors of the various built-in, high-voltage RC filters. Consequently, parasitic ac voltages from the parts of the cascade rectifier conducting ac voltages (from the high-voltage transformer and from the capacitor stack) are transmitted via the natural stray capacitances between the parts of the structure to those parts of the installation which should only conduct dc voltages. In an air-insulated installation, necessary ripple, which must be reduced to the order of 1 x  $10^{-6}$  of the accelerating voltage, cannot be achieved.

### The Twin-Tank Accelerator

In the pressurized accelerator, which is distinguished by the twin-tank structure, the cascade generator and the accelerator system are accommodated in separate steel tanks. In this way, parts of the installation which carry dc and ac voltages are separated electrostatically and protected from each other. A pressure tube joins the two tanks at the top terminals of the generator and accelerator. Through the center of this pressure tube runs a high-ohmic damping resistor, which connects the two parts of the installation electrically. In Fig. 2, the upper parts of the pressure tanks and the connecting tube are removed. The damping resistor is so arranged in the connecting tube that, in the event of flashover in the accelerator, it is able to withstand the full dc voltage. The coupling capacitance between the high-voltage terminals of the generator and the accelerator is the least possible; and, by means of the stray capacitances between the damping resistor and the walls of the pressure tube, a very effective RC filter results.

The twin-tank design was developed in 1967 and was introduced as a commercial 1 MeV accelerator for the EM 7 electron microscope of AEI Scientific Apparatus Ltd. A detailed description of that equipment was the subject of a contribution to the 1969 Particle Accelerator Conference.

### Electrical Circuit of the Twin-Tank Accelerator

The schematic diagram in Fig. 3 is considered typical for the generation and regulation of high voltage for the different models of the twin-tank accelerator. The accelerating voltage is generated by a symmetrical cascade generator and applied to the accelerating tube via the high-ohmic damping resistor.

The natural stray capacitances between the damping resistor and the wall of the pressurized connecting pipe are shown in dotted lines to emphasize that this system represents an iterative filter network.

Parallel to the accelerating tube, an ohmic voltage divider provides a linear voltage



Fig. 2: Pressurized 1.2 MeV Electron Accelerator, Twin-Tank Design EM 7, AEI Scientific Apparatus Ltd, Harlow, England



Fig. 3: Schematic Circuit Diagram 1.5 MeV Twin-Tank Accelerator

distribution to the accelerating electrodes. The accelerating voltage is measured by a precision ohmic-capacitive voltage divider and compared with a reference voltage which can be set remotely according to the desired value of the accelerating voltage. When the accelerating voltage fluctuates, error signals are given as a result of the difference between the secondary output voltage of the precision voltage divider and the reference voltage. These error signals are amplified in ac and dc amplifiers, thereby affecting the amplitude of the medium-frequency voltage of the RC oscillator in the modulator. Thus, ac voltage is fed into the power amplifier, which is directed against the fluctuations in the accelerating voltage. The power amplifier feeds the high-voltage transformer of the symmetrical cascade generator.

The high-voltage transformer of the symmetrical cascade generator of the twin-tank design is fitted with an additional measuring coil on the primary side. Its output voltage is rectified and applied to the modulator via a filter link. This feedback circuit is required because of the high stray inductance and, therefore, high impedance normally shown by high-voltage transformers for medium frequency. The effect of this additional control circuit presents itself in an apparent lowering of the impedance of the high-voltage transformer.

### Improvements of the Twin-Tank Accelerator

With the increasing number of commercial high-voltage electron microscopes installed in different countries and in view of the trend towards higher voltages and improved resolving power, up-graded models of the electron accelerator were developed. One may now choose between maximum operating voltages of 1 MV, 1.2 MV, and 1.5 MV. With respect to stability, the standard model has an overall stability of  $+ 1 \times 10^{-5}$ . Another model with improved stability has a figure of  $\pm$  5 x 10<sup>-6</sup>; and in the model with the greatest stability, a short-time stability of  $\pm 1 \times 10^{-6}$  has been achieved. These stability figures are for time periods of three minutes, which is the maximum time required for setting the microscope controls, the direct viewing of the image, and the exposure of the micrographs.

The only difference in design or physical dimensions for the electron accelerators at 1.0 MeV and 1.2 MeV are the voltage controls. The higher operating voltage is achieved by reducing the overvoltage which may be applied to condition the accelerating tube. Actually, both accelerator models may be operated up to 1230 kV for conditioning the accelerator. The additional conditioning voltage available determines the operating hours during which performance of the accelerating column without micro-discharges may be expected. For the 1.5 MeV accelerator, both the high-voltage generator and the accelerator structure were extended in voltage by increasing the number of stages, but without any change in the physical dimensions of the pressure vessels. This was achieved by increasing the pressure of the sulfur-hexa-fluoride insulating gas in the tanks from 60  $lbf/in^2$  to 90  $lbf/in^2$ . The conditioning voltage of the accelerating tube which may be applied is 1600 kV.

The improvement in stability was partially achieved by using resistors of superior quality for the ohmic-capacitive voltage divider which controls the regulating circuits. In developing improved voltage dividers, the noise levels generated in the individual resistors of different kinds were compared by measuring the current fluctuations in a bridge circuit. The following lowfrequency noise figures were established:

wire-wound resistor	1	x	10 <sup>-6</sup>
cermet type (metal glaze)	8	x	10 <sup>-6</sup>
carbon resistor	25	x	10 <sup>-6</sup>

Another important improvement in voltage stability was achieved by utilizing solidstate units in the electronic regulating circuit and by developing a solid-state reference-voltage supply. Practical experience has shown that the stability of the reference-voltage source must be 5 to 10 times greater than the desired stability of the accelerating voltage. The new referencevoltage source utilizes a Zener diode with a temperature coefficient of 10 ppm/degree centigrade which is thermostatically held at a fixed temperature within 1/100 of a degree centigrade. The stability of the reference voltage is  $1 \times 10^{-7}$  during the critical time period of three minutes.

Other minor modifications were made, and a new system for the filament supply of the electron gun was introduced. In the first models, the filament was energized from a bank of nickel-cadmium batteries. The batteries required recharging and showed a failure rate which was low but, nevertheless, unacceptable for an instrument which was designed for particularly high reliability. The filament is now supplied through a highfrequency transmission system, the principle of which is also shown in Fig. 3.

#### Future Trends

In general, the electron microcopists are calling for higher voltages and even greater stability.



Fig. 4: EM 7 Microscope with 1.2 MeV Electron Accelerator at AERE, Harwell, England

The principle of the twin-tank design can be easily applied to much higher voltages. Voltages above 8 MV can be achieved with the symmetrical Cockcroft-Walton generator, which employs the voltage-multiplying principle. Above 8 MV, however, some materials in the electron microscope would become radioactive under the electron bombardment. The output voltage of the Cockcroft-Walton circuit of the simple or symmetrical design is given by the formula:

$$V = 2 N V_{ol}$$
(1)

where V = peak voltage of the high-voltage transformer, and N = number of stages.

From formula (1), it appears that any desired voltage could be achieved by increasing the number N of stages. However, the transport of charges from the bottom stage to the topmost stage of the generator through all the capacitors of the circuit causes a significant voltage drop which, for the symmetrical cascade generator, is given by the formula:

$$\Delta V = \frac{I}{fC} \left( \frac{N^3}{6} + \frac{N}{3} \right)$$
 (2)

where I = load current, f = operating frequency, and C = capacitance per capacitor.

As the output voltage V increases linearly with the number N of stages, whereas the voltage drop  $\Delta$  V grows with N<sup>3</sup>, it is evident that from a certain number of stages the gain in output voltage is more than compensated by the increase in voltage drop.

With the following conservative figures for the example of the 8 MV cascade generator:

I = l mA (to provide the beam current and the currents through the bleeder potentiometer and the measuring potentiometer),

$$f = 10 \text{ kHz},$$
  
C = 2000 pF, and

N = 40

the formula (2) yields a voltage drop V of 500 kV, which is very reasonable as compared to the total output of 8 MV.

For the symmetrical cascade rectifier, the ripple voltage is represented by the formula:

$$S V = \frac{I}{fC} - \frac{1}{2} N, \qquad (3)$$

and it is found that the ripple voltage is 1 kV from peak to peak under full load. That figure is too high by a factor 100 and, therefore, the result suggests the use of the twintank design to insert a very effective filter circuit.

### References

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