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PRESSURIZED 1-MeV ELECTRON ACCELERATOR OF THE TWIN-TANK DESIGN FOR ELECTRON MICROSCOPY

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Summary

A pressurized 1-MeV electron accelerator was developed after the principle of the symmetrical cascade generator with fully electronic ac supply and voltage regulating systems. A special feature of the new commercial model is the twin-tank design in which the high voltage generator and the accelerator are separated from each other in individual tanks. The two units are connected by a high-ohmic resistor which is enclosed in a pressurized connecting tube. The ripple voltage is negligible (1×10^{-7}) and the overall voltage stability is between 1×10^{-6} and 1×10^{-5} in the voltage range from 100 kV up to 1 MV. The electron accelerator is designed as a production model for the supply of a commercial 1-MeV electron microscope.

Introduction

During the last decade a new generation of high voltage electron microscopes began operation, using accelerating voltages in the 1-megavolt range, i.e. ten times the voltage of conventional instruments. A great leap forward was achieved by these research instruments both in the field of electron microscopy itself and the application of the new powerful equipments in biology, metallurgy and metal physics.

The chief gain in the application of higher voltages in electron microscopy results from the fact that interaction of electrons with matter decreases. [1] This reduces the effect of chromatic aberration and radiation damage, improves image resolution (for a specimen of given thickness) or increases the effective penetration of the specimens.

The first high voltage electron microscopes were designed to investigate their electron optical properties, prove existing theories on electron microscopy or establish new ones, image living microorganisms inside micro-chambers with plastic windows and study the structure of bulk metal as a benefit of greater available penetration. Basically, those high voltage microscopes are scaled-up models of the ordinary commercial 100-kV instruments, all physical dimensions being enlarged roughly in proportion to the square root of the maximum operating voltage. [1] A more serious problem involved in high voltage electron microscope design is radiation protection from X-rays. A new and significant design feature is the replacement by a dc accelerator of the relatively simple electron gun which is being used in conventional instruments. In principle, the accelerators are of the same design as those for nuclear research, except that electrons are accelerated instead of ions. A short-time voltage stability of the order of 1×10^{-5} is required from the accelerator to make chromatic aberration in the microscope lenses negligible. The ordinary or the symmetrical cascade generator plays a dominant role in this particular application because of the extremely high stability in accelerating voltage which can be achieved by utilizing fully electronic ac supply and regulating systems and because of the absence of vibrations, which is an absolute necessity in electron microscopy.

Design Considerations

The first dc accelerators for high voltage electron microscopy were all of the air-insulated or so-called open design. [2,3] They offered the great advantage of ready access to all components which allowed to cut the break-down time required for modifications, servicing or repairs.

From the performance of these electron accelerators the unexpected conclusion was reached that the practical limit of voltage stability was set by the residual ripple voltage rather than by the efficiency of the regulating system. It was found that an additional ripple voltage originated from the high ac voltage which appears at the supply transformer and the coupling capacitors of the cascade generator and is transmitted through stray capacitances on to the components of the accelerator stack. Obviously, the problem of interference between the cascade generator and the acce-

lerator stack becomes more significant with a pressurized accelerator of compact design in view of the even closer proximity of those incompatible electrical components which carry either high ac or dc voltages. The methods of high voltage generation which are employed at present for electron microscope accelerators, such as ordinary or symmetrical cascade rectifiers and Insulated Core Transformers, will not allow one to achieve such high a voltage stability with the high voltage dc power supply and the accelerating tube enclosed in a common tank. For this reason, it was decided in the layout of the commercial model of the pressurized 1-megavolt accelerators to separate and shield the cascade generator and the accelerator stack from each other by using two tanks with a so-called bus-bar connexion, i.e. a high-ohmic damping resistor between the high voltage terminals of the dc generator and the accelerator which is enclosed in a connecting tube between the two pressure tanks. This twin-tank design provides a perfect shielding of the accelerator stack from the ac influences of the high voltage dc power supply.

1-MV Cascade Generator (Fig. 1)

A symmetrical cascade rectifier is employed to generate the accelerating voltage. It consists of two high voltage transformers, two columns of coupling or ac capacitors, and one column of smoothing or dc capacitors. The symmetrical cascade generator has 8 stages each of 150 kV dc with a total of 32 high voltage rectifiers for 1.2 MV maximum voltage.

In the individual stages the corresponding ac capacitors of the two coupling columns are connected through compensating chokes. Without these chokes excessive capacitive currents would be created due to the stray capacitances between the ac columns and ground. Those capacitive currents would overload the high voltage transformers and the electronic ac supply system. The compensating coils are in parallel with the stray capacitances and matched in their inductance that the resulting impedance is infinite at the operating frequency of the generator. Thus, the capacitive current drawn from the high voltage transformers is minimized.

The symmetrical cascade generator is enclosed in a steel tank 10.5 ft high and 6.5 ft dia. Sulfur hexafluoride at 60 lbf/in^2 serves as insulating gas for the entire accelerator. The accelerating voltage is applied to the high voltage terminal of the accelerator stack through the high-ohmic damping resistor, which combined with its stray capacitance to the wall of the connecting tube, forms a very efficient filter network to reduce the ripple voltage. This voltage which appears at the accelerator terminal is negligible. It was measured to be 0.1V at 1 MV and full load.

Electron Gun and Accelerator (Fig. 1)

The accelerator tank is 8.7 ft high and 6.5 ft dia. It includes the electron gun, the accelerating tube, the ohmic-capacitive voltage divider of the regulating system and a set of 8 insulating shafts for the remote control of the injector system. Conventional elements, such as a pinpoint cathode, Wehnelt electrode and anode are utilized in the electron gun. The critical dimensions and the geometrical arrangement are designed for maximum brightness. To extend the operating time of the electron gun a turret is provided which accepts 6 cathode cartridges. The accelerator tank is available with two different systems for the replacement of the burnt-out cathodes. A man-hole with a cover plate at the top of the pressure vessel permits access to the electron gun through a large opening in the accelerator terminal. However, access is only possible under normal atmosphere after the insulating gas has been pumped back into the storage tank. The other more convenient and less time consuming system uses a gas lock. Replacement of the cathode turret is possible even under full pressure of the sulfur hexafluoride. During a turret change there is a loss of only 0.5 lb insulating gas. The gun filament is energized from a gas and pressure tight nickel-cadmium battery with a total capacity of 720 ampere-hours, which is sufficient for 240 hours of continuous operation. The batteries are recharged under full gas pressure during the servicing periods of the equipment. For recharging, the batteries are switched to the battery charger at ground potential through a pair of telescopic connectors which are remotely controlled and extend from the accelerator base to the high voltage terminal.

The accelerating tube is composed of 24 stages each of 50 kV dc. The isolators of the accelerator column are made of

porcelain rings which are cemented together to build sections of 200 kV. The 200-kV-sections are sealed together by metal flanges and O-rings. The mumetal accelerating electrodes are cone-shaped and overlap in such a way that the entire path of the electron beam is covered and shielded from the influence of the earth's magnetic field. The accelerating electrodes are connected to a bleeder-chain in parallel with the beam tube to provide a linear voltage distribution. The Wehnelt electrode and the anode of the electron gun are fed from the same dividing resistor. By this method the ratio remains constant between the accelerating voltage and the anode voltage. Therefore, the final cross-over in the electron beam delivered to the microscope column is kept sufficiently stationary over the extremely wide range of operating voltage from 0.1 MV to 1.0 MV. By suitable choice of the resistance of the anode voltage potentiometer the position of that cross-over can be fixed at any distance from the bottom end of the accelerating tube to infinity.

The extremely wide variation by the factor 10 of the accelerating voltage poses the problem that the anode voltage will become insufficient at the lower end of the voltage range to establish the surface field strength required at the cathode tip to achieve a high brightness. To overcome this disadvantage a remotely controlled magnetic device is incorporated in the electron gun which automatically raises the anode closer to the cathode as the accelerating voltage decreases below 300 kV.

Typical brightness figures as measured at a distance of 4.5 ft from the bottom end of the accelerating tube are:

Accelerating Voltage kV	Beam Current μA	Brightness $A/cm^2 \times sr$
100	114	1.2×10^5
400	33	1.6×10^6
700	21	4.0×10^6
1000	18	1.3×10^6

The functions of the electron gun are remotely controlled from ground potential through insulating shafts which are driven by servo-motors. These controls include:

beam current on and off,
beam current coarse,
beam current fine,
filament current fine,
x-deflection,
y-deflection,
anode adjustment,
cathode change.

The relatively great variety of independant controls provides a particular flexibility to the microscope operator for the adjustment of the gun parameters.

The vacuum system mainly consists of the vacuum manifold between the accelerating tube and the microscope column, a Pfeiffer turbomolecular pump with a pumping speed of 260 l/s and a backing pump with a pumping speed of 9 ft^3/min. A metal bellows of high flexibility is inserted between the turbomolecular pump and the manifold to damp the extremely small vibrations of the rotating pump.

With the increase of accelerating voltage electron microscopists have experienced micro-discharges in the accelerating tube, i.e. fast fluctuations of the voltage by a few tens or hundreds of volts after hours of operation. The micro-discharges create short-time instabilities in voltage and should therefore be avoided, in particular during the exposure time of micrographs. Whether or not these micro-discharges will occur depends on the conditioning state of the accelerating tube. Immediately after conditioning dischargefree performance is possible for a period of at least a few hours. The conditioning state deteriorates over a longer period of time and the accelerating tube has to be reconditioned at a higher voltage than at which it is intended to operate. To extend the continuous operating time of the microscope at the rated voltage, the high voltage dc power supply and the accelerator are designed for a maximum voltage of 1.2 MV.

AC Supply and Regulating System (Fig. 2)

The ac supply and regulating systems of the symmetrical cascade generator are fully electronic. The operating frequency of the cascade rectifier is generated by a RC oscillator the output voltage of which is applied through a driver chain to the grids of the electron tubes in the power amplifier that feeds the high voltage transformers. The power amplifier is energized from a 3-phase full-wave rectifier using silicon diodes.

Two regulating loops are designed to stabilize the accelerating voltage. The dc output-voltage is measured by an ohmic-capacitive voltage divider of very high precision. The resistive part of the voltage divider is made of wire-wound resistors with a temperature coefficient of 1×10^{-5} per degree centigrade. The output or secondary voltage of the divider is compared with a reference voltage of high stability. The reference voltage is obtained from a voltage source, based upon a special glow discharge tube which is immersed in oil. This oil is thermostatically controlled. To set the reference voltage and the accelerating voltage to the required value either a multiturn helipot or a chain of fixed precision resistors is used depending on whether a continuous or stepwise adjustment of the dc output voltage is required.

Deviations between the output signal of the divider and the reference voltage, i.e. error signals, are amplified in ac and dc amplifiers, combined in a mixer amplifier and utilized in the modulator to modulate the amplitude of the output voltage of the oscillator in such a way that the ac input voltage of the transformers nullifies the fluctuations of the accelerating voltage.

High voltage transformers usually have a high stray inductance due to their bulky insulation. The stray inductance produces a large inductive voltage drop as a function of the load. To reduce the effect of high impedance of the supply transformers a second feed-back loop is inserted. From a third winding on the transformers an ac voltage is obtained which passes through a rectifier and filter circuit and controls the modulator.

Controls

The electronic equipment and the control units are built in standard 19" racks. The main controls and meters are duplicated at the microscope console for the convenience of the operator. In the new commercial model the electron microscope and the accelerator are designed for automatic operation. The desired accelerating voltage of the microscope can be set by means of 11 push-buttons from 0 kV up to 1 MV in 100-kV steps. With the selection of the operating voltage the beam current of the accelerator and the current supplies of the magnetic lenses in the microscope are simultaneously and automatically set to their required values.

Besides the automatic operation scheme of the microscope it is possible to switch over to other modes of operation. The accelerating voltage can be continuously raised up to 1.2 MV for conditioning purposes. The electron gun can deliver larger or lower beam currents at any accelerating voltage between 100 kV and 1000 kV. A maximum beam current of 200 μA is available at all voltages to irradiate specimens. Thus, the equipment offers both great ease of operation for routine work and a wide flexibility for special research applications in electron microscopy.

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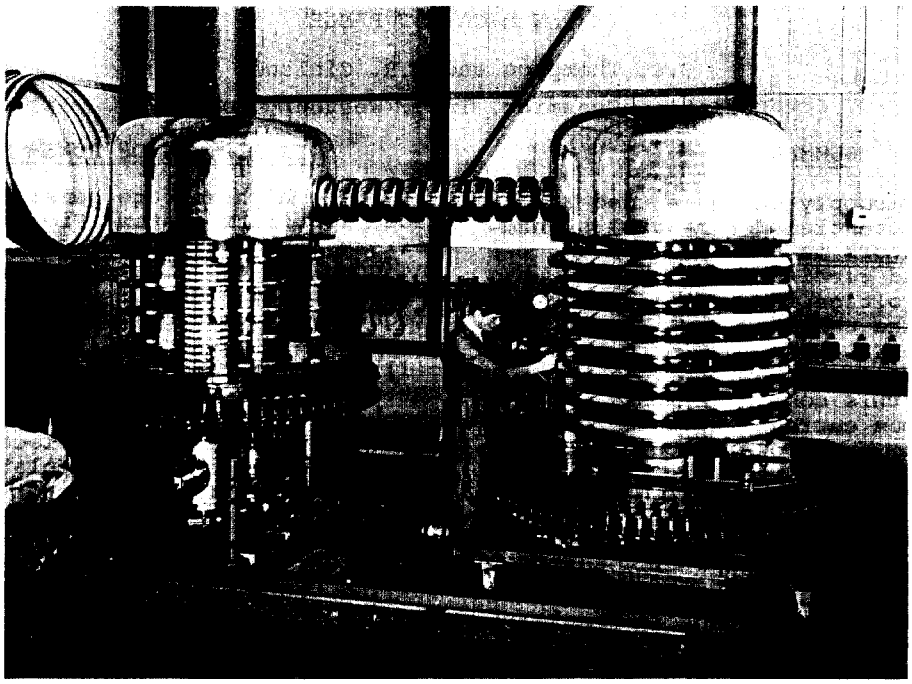


Fig. 1. Accelerator stack, damping resistor and cascade generator of the 1-MeV electron accelerator.

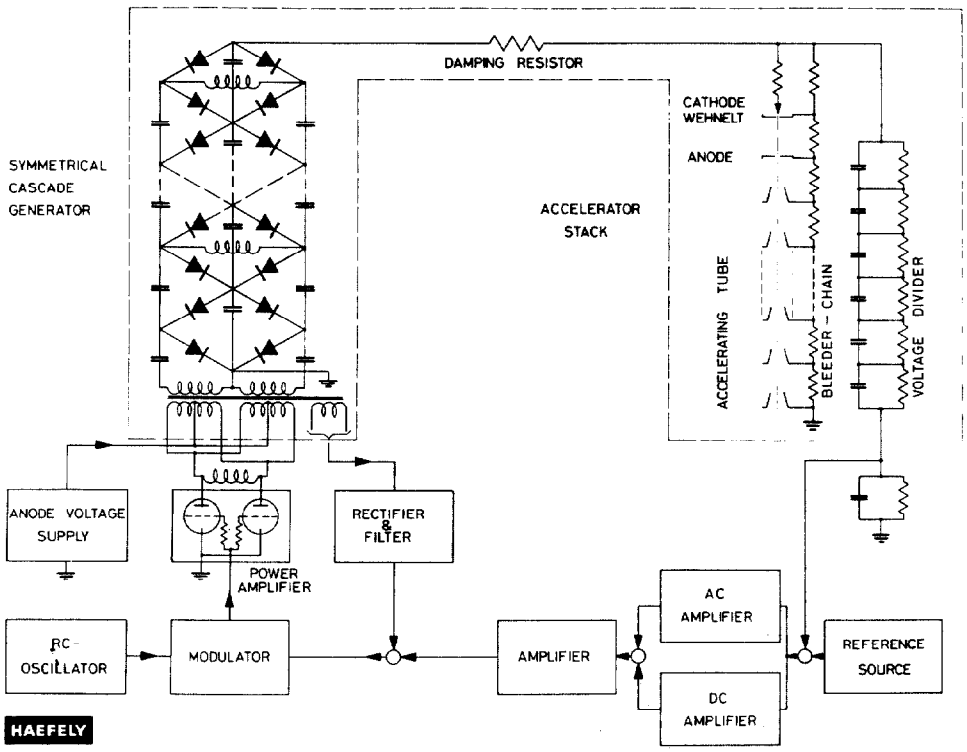


Fig. 2. Block diagram of the 1-MeV electron accelerator