Accelerator system for 1-MV STEM*

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The accelerator, magnetic shielding–equipotential grading system, and voltage divider chain of the University of Chicago 1-MV STEM are described. A dynamical analysis of the system is presented in addition to a discussion of the problem of "electron loading" encountered while conditioning the accelerator tube.

MAGNETIC SHIELDING AND EQUIPOTENTIAL GRADING SYSTEM

Magnetic disturbances can seriously degrade the performance of an electron microscope. Although scanning microscopes are somewhat less sensitive to such disturbances as a result of synchronizing each line of the scan with the power line cycle, the problem is not completely eliminated by this technique. First, the disturbing field may vary during the sampling time at each point comprising a scan line, and second, if the disturbing fields are not small compared to the scanning fields, a significant distortion may be introduced.

Two approaches immediately suggest themselves for minimizing magnetic disturbances: shielding the beam path and keeping the beam path length as short as possible. Although both approaches may be successfully followed for low-voltage microscopes, the problem becomes nontrivial at high voltages.

In the 1-MV STEM at the University of Chicago[1] the accelerator path length has been reduced to 57 cm, utilizing a National Electrostatics Corporation three-section all metal and ceramic accelerator with titanium electrodes. Magnetic shielding was achieved by constructing the equipotential grading column from a set of coaxially nested μ-metal[2] disks separated by Plexiglas insulators which are electrically connected and serve also to support the grading resistor–voltage divider chain. The divider chain is arranged in a spiral which winds about the accelerator in the gap between the μ-metal disks (see Fig. 1). The horizontal component of the disturbing field (perpendicular to the axis of the accelerator), which falls off exponentially[3] between the disks, has been reduced to 1 μG on axis. The actual shielding factor was rather difficult to measure as the most sensitive probe available was 0.33 V/G at 60~, i.e., the external field had to be increased to a point in the saturation region of the μ-metal. A minimum shielding factor of 3000 was obtained under these conditions.

VOLTAGE DIVIDER CHAIN

The voltage divider chain is composed of 198 resistors, each having a resistance of 500 MΩ and a voltage rating of 5000 V (Victoreen MOX-1125). Three resistors, a total of 1500 MΩ, are used between each two μ-metal disks except in the decoupling regions between accelerator tube sections (cross hatching, Fig. 1), where shorting links are used. At 1 MV the current drain is 10 μA.

Such divider chains have often presented design difficulties in that they tend not to survive voltage surges.[4] This has not been a source of difficulty in the present design, which has survived numerous discharges and operated successfully at 1.1 MV, primarily because of the capacitive effects of the magnetic shielding disks. This can be understood by noting that the voltage divider chain initially has the step function response of a pure capacitive divider with cross and ground capacitances (Fig. 2). The cross capacitance, which appears across the divider resistors, is essentially that between the μ-metal plates; the ground capacitances, C_g, are due to the stray capacitance of the μ-metal plates to the pressure vessel wall housing the accelerator system. In general,[5] for a symmetrical network of this type

$$V_m = V_n \cosh[(n-m)\gamma] + I_n Z_0 \sinh[(n-m)\gamma], \quad (1)$$

where

$$V_m/V_{m+1} = e^{\gamma}. \quad (2)$$

γ is the propagation function which, for the mth to nth sections, is $(n-m)\gamma$. V_m and I_m are, respectively, the voltage and current inputs to the mth section, and V_n and I_n are the outputs of the nth section. Z_0 is the characteristic impedance. For a short-circuited termination, $V_n = 0$ so that

$$V_m = I_n Z_0 \sinh[(n-m)\gamma], \quad (3)$$

and for $m = 0$,

$$V_0 = I_n Z_0 \sinh(n\gamma) \quad (4)$$

Eliminating I_n between Eqs. (3) and (4),

$$V_m = V_0 \sinh[(n-m)\gamma]/\sinh(n\gamma). \quad (5)$$

For the symmetric π filter comprising the units of the capacity divider chain in Fig. 2,

$$\cosh\gamma = 1 + C_g/2C. \quad (6)$$

If there is little attenuation along the chain (an assumption which will be found to be reasonable for the present case), the expansion of $\cosh\gamma$ in a series,

$$\cosh\gamma = 1 + \gamma^2/2! + \ldots = 1 + C_g/2C,$$

yields

$$\gamma \approx (C_g/C)^{1/2} \quad (7)$$

For the present system $n = 66$, $C \sim 1500$ pF, $C_g \sim 1$ pF. The network time constant is then about 5 sec, and $\gamma \sim 0.026$.

The quantity of interest is

$$V_m/V_0 m^{-1} = m \sinh[(n - m)\gamma]/\sinh(n\gamma), \tag{8}$$

which measures the deviation of the voltage distribution from a linear one. For $m = n - 1 = 65$, the worst case, $V_m/V_0 m^{-1} \sim 0.6$.

The capacitance of the magnetic shielding assembly is thus seen to be very helpful in stabilizing the voltage distribution on the accelerating electrodes.

Vernon Beck, presently with the Enrico Fermi Institute of the University of Chicago, has successfully compensated a precision 100-kV resistive divider to within 10% from dc to 100 kHz by using the following technique: In Fig. 2 let the cross capacitance C of the mth section be denoted by C_m. Impose now the following conditions of voltage linearity on the divider network:

$$\begin{aligned} V_{n-1} &= V_{n-2}/2, \\ V_{n-2} &= 2V_{n-3}/3, \\ &\vdots \\ V_{n-l} &= lV_{n-(l+1)}/(l + 1) \quad (0 \le l < n). \end{aligned} \tag{9}$$

We are here considering the original constant cross capacitances C to be zero and calculating those values of cross capacitance C_m needed to linearize the network; i.e., given the existence of the ground capacitances C_g, we will determine what values of cross capacitance yield a linear network. With no loss of generality C_n may be set equal to zero. Consider now the first of Eqs. (9). Looking from V_{n-2} to ground we see that $V_{n-1} = V_{n-2}/2$ if $C_{n-1} = C_g$. The second of Eqs. (9) will be satisfied if C_{n-2} is such as to have twice the capacity as the point V_{n-2} to ground; i.e., $C_{n-2} = 2[C_g \| (C_g + C_g)] = 3C_g$. The symbol "+" here means "in series with." Proceeding in this way we arrive at the set of values:

$$\begin{aligned} C_n &= 0, \\ C_{n-1} &= C_g, \\ C_{n-2} &= 3C_g, \\ &\vdots \\ C_{n-l} &= (l/2)(l + 1)C_g. \end{aligned} \tag{10}$$

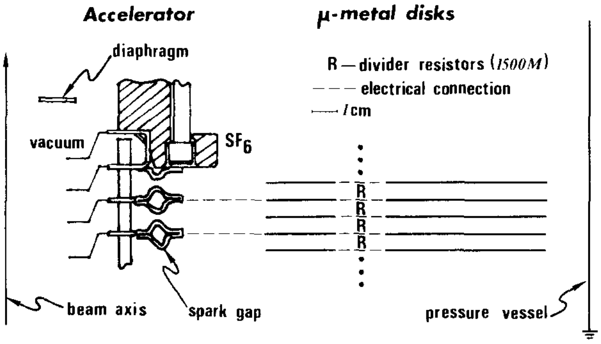

FIG. 1. Schematic representation of part of the magnetic shield–equipotential grading system and voltage divider chain. The beam axis is the axis of cylindrical symmetry for the figure. Note that the distance to the pressure vessel is not to scale.

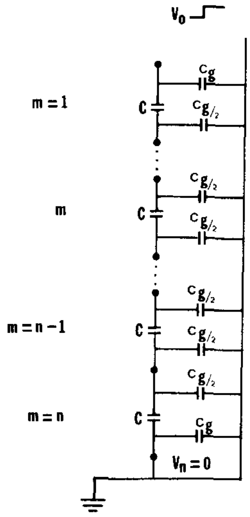

FIG. 2. Initial appearance of the voltage divider chain to a step function. C_g is the stray capacitance to ground of one μ-metal disk; C is the capacitance across the divider resistors between disks. C_g has been split into two parallel components, each of value $C_g/2$ in order to emphasize the symmetric character of the units comprising the network.

Consider now another chain of equal capacitors with no ground capacitances. Such a chain is linear. A chain consisting of ground capacitances C_g and cross capacitances given by Eqs. (10) is also linear. Since both networks are linear, corresponding points may be connected without changing the response; that is, a constant may be added to each C_m. In this way it is seen that the constant cross capacitances, which were previously ignored in order to facilitate the calculation of the values given by Eqs. (10), do not affect the values of the capacitors needed to compensate the network. This method of compensation fails when the idealization of Fig. 2 no longer holds, i.e., at frequencies such that inductive effects become significant.

ELECTRON LOADING OF THE ACCELERATOR[4,6]

Electron loading of accelerator tubes, although known since at least 1951,[7] has not yet found a satisfactory explanation. From the "long tube effects"[6,8] one may, however, conclude that electron loading is a multisection, multiplicative process. One mechanism, which explicitly assumes that secondary electrons produced in the accelerator tube wall are responsible for the effect, is given by Boyd and Kane[9] along with a mechanism to suppress such avalanches. It is not presently clear if this mechanism would apply in our case since the insulating surfaces of the accelerator wall are well shielded from primary electrons by the use of cupped electrodes.

Cranberg and Henshall[10] found that the sustaining voltage of an accelerating tube may be made proportional to its length by the periodic introduction of small aperture diaphragms. The National Electrostatics accelerator is designed to operate with two such diaphragms. We found that they decrease the peak x-ray production by about an order of magnitude. The electron loading effect presently limits the conditioning rate near 1 MV to 20–50 kV/h.

If electron loading is indeed a multisection, multiplicative process involving the accelerator electrodes and/or wall, then the source of the steady current cannot be ignored, and we may expect the voltage distribution of the divider chain to be affected. The situation is analogous to the variation of potential difference along the voltage divider of a photomultiplier tube under conditions of large photocurrents, i.e., when the anode current is comparable to the divider current. The effect is to increase the potential across the upper (terminal end) accelerating electrodes by the product of the divider resistance between the electrodes and the loading current, and similarly, to decrease the voltage across the lower electrodes. Since the loading increases with the sixth power of the voltage,[7] this effect can rapidly become significant.

These considerations serve to emphasize the fact that the accelerator cannot be treated in isolation but must be considered both statically and dynamically in conjunction with both its equipotential grading system and voltage divider chain.

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