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"Multi-Loop Feedback System for Dynamitron Voltage Regulation"

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Summary

The stability of the Dynamitron high voltage generator is influenced by several factors: 1) beam load changes, 2) changes in the power mains, 3) frequency components in d.c. anode power to the oscillator tubes, and 4) modulation due to a.c. heated filaments. A brief analysis based on experimentally obtained data and the reasons for stabilizing the generated voltage by means of a multi-loop feedback system are presented.

Measurements made on a 3.0MeV accelerator show that terminal ripple is 1500 volts peak-to-peak and that the regulation from zero to six milliamperes of beam is less than ±1500 volts. Future improvements in the generator and regulating electronics design should result in reducing the ripple to 600 volts peak-to-peak and the regulation to ±600 volts.

Introduction

The Dynamitron, a potential drop accelerator, is designed for voltages up to 4 Mv either for ions or electrons. The unique features are: 1) the ability to supply high beam powers, 2) a low-stored energy system, and 3) the capability to attain a high degree of voltage stability.

This paper covers a description of the high voltage generator, the r.f. oscillator, the voltage regulating system, factors influencing voltage stability, and results of measurements made on a second-generation 3.0 Mv ion accelerator delivered to Ottawa Carleton Universities.

System Description

The high voltage generator is a cascaded rectifier system, Figure 1, whose rectifiers are parallel-fed through the inherent coupling capacitance C, created by the corona shields and the r.f. electrodes. The prime mover is a high-power r.f. oscillator, operating at approximately 130KHz. The tank circuit is made up of the high Q toroidal inductance L, which is designed for r.f. voltage step-up, and the r.f. electrode to pressure vessel capacitance C_t. The oscillator is a tuned-plate untuned-grid circuit whose frequency is determined approximately from the relationship $f = 1/2\pi\sqrt{LC_t}$, neglecting the effect of C, the coupling capacitance. The oscillator tube receives its grid drive from a plate located outside the r.f. electrode. The r.f. amplitude is controlled by varying the voltage, E_p, on the oscillator tubes anodes by means of series-pass tubes. A cathode follower driver supplies the necessary grid current for the series-pass tubes. Control voltage to the cathode follower driver is supplied by a grounded-cathode tetrode. E_p is stabilized by negative feedback from the output of the series-pass tubes to the input of the amplifier, K_2. This inner feedback loop, E_p/V_1, makes rapid corrections for variations in E_p due to changes in the supply mains and also acts as a high attenuation dynamic filter. The generated high voltage, E, is stabilized by an outer feedback loop, V_F/E_R, from the voltage divider board, R_D, which develops a voltage, V_F, across R_F. This voltage is summed with the reference voltage, E_R, of opposite polarity. The error signal is amplified by K_1 and the feedback loop is closed by connecting the output of amplifier K_1 to the input of amplifier K_2.

Closed Loop Regulating System

The schematic diagram, Fig. 1, is represented in block diagram form in Fig. 2. The values and descriptions of the transfer functions are given in Table I.

The derived transfer function of the inner-loop is:

$$\frac{E_p}{V_1} = \frac{R_5/R_3}{1+P(C_3R_5+C_2R_4/K_2(R_3/R_5))+P^2C_2R_4C_3R_3/K_2}$$

$$= \frac{100}{(1+1.32\times10^{-5}P)(1+11.3\times10^{-9}P)}$$

To investigate the effect of variations of E_{dc} upon E_p it is necessary to look at the function E_p/E_{dc}. The derived expression is:

$$\frac{E_p}{\pm nE_{dc}} = \frac{(1+PC_2R_4)(1+PC_3R_3)}{K_2K_3K_4K_5K_7\{1+P(C_3R_5+C_2R_4R_5/K_2R_3)+}$$

$$\overline{P^2C_3R_5C_2R_4/K_2\}}$$

$$E_p = \frac{\pm nE_{dc}(1+25\text{x}10^{-7}P)(1+1.2\text{x}10^{-7}P)}{140(1+1.32\text{x}10^{-5}P)(1+1.13\text{x}10^{-9}P)}$$

The term n represents the fractional variation in E_{dc} due either to inherent ripple or changes in the a.c. supply mains. The main ripple in the d.c. supply is 15 percent peak-to-peak at 360 cps. Since the frequency dependent terms can be neglected at this frequency the ripple would be attenuated to:

$$E_p = \frac{\pm\, 0.075E_{dc}}{140}$$

$$= \pm 5.3\text{x}10^{-4} \text{ or } 0.106 \text{ percent peak-to-peak}$$

Higher frequency components like those contained in a power line transient would experience similar attenuation, governed by the frequency dependent terms.

The outer-loop, V_F/E_R, which regulates the terminal voltage, E, for changes in beam load, has a slow response of 0.2 sec. The response of this loop is determined by the non-linearity of the high voltage generator. The transient response of the rectifier cascade in increasing the terminal voltage or charging the terminal capacitance, C_D, is limited by the transport charge time of the rectifier cascade and the maximum instantaneous charge per rectifier stage. The transport time is directly proportioned to the number of stages, N, and is inversely proportioned to the frequency, f. The transient response for decreasing terminal voltage is determined by the discharge time of the terminal capacitance, C_D, and the effective load, since the rectifier cascade is a unilateral device and cannot carry charge away from the terminal. The limitation of response is governed by the discharge time which is $T_{10} = R_LC_D$, where R_L is the sum of the resistance boards and the effective resistance due to the voltage, E, and beam current, I, or E/I. The worst case is when the beam current is zero, where $T_{10} = 0.6$ sec. The loop must have a unity gain at a cross-over frequency of $\omega \approx 1/0.6$ in order to be stable. To provide sufficient loop gain below the cross-over frequency a high-gain chopper-stabilized d.c. amplifier with frequency sensitive feedback is used. This feedback network is such that at d.c. the loop gain is approximately 10^4v/v and at $\omega = 1.6$ the gain is 1. The derived closed loop transfer function E/E_R, neglecting frequency dependent terms above $\omega > 1.6$ since they are more than a decade higher, is:

$$\frac{E}{E_R} = \frac{1}{K_{11}K_{12}(1+PT_1K_{8-12}/K_7)}$$

$$= \frac{5\text{x}10^4}{1+0.195P}$$

The voltage regulation due to beam load can be determined by writing the closed-loop E/E_R for the load and no-load case. Neglecting the a.c. response of the system.

$$E/E_R = G/(1+GH)$$

$$E'/E_R = G'/(1+G'H)$$

Where primes represent the change due to load, and

$$G = K_1(1/K_7)K_8K_9K_{10}$$

$$G' = K_1(1/K_7)K_8K_9K_{10}(1+IZ/Eo)$$

The percent regulation is:

$$\%\ \text{Reg} = \frac{E-E'}{E}\text{x}100 = \frac{G-G'}{GG'H}\text{x}100$$

$$= \frac{-IZ/Eo}{8600(1+IZ/Eo)}\ \text{x}100$$

Assuming a 10 milliampere beam at 3 Mv and a cascade impedance, Z, of 24 megohms, the regulation is:

$$\text{Reg} = 9.3\text{x}10^{-4}\%$$

This is an extremely low value which experimentally has not been attained. In a practical sense the regulation, measured by monitoring the change in E_F due to beam current, is obscured by system noise due either to amplifiers or to corona currents on the resistor board. This is further aggravated by ion beam current, since backstreaming electrons striking dynodes in the accelerator tube create X-rays which ionize the insulating gas. Nevertheless, the regulation with noise is less than 0.1 percent. These measurements are discussed further in the next section.

The ripple voltage due to the carrier frequency is a function of the last rectifier stage and is given by:

$$\Delta E=(I/fC'K)/\omega^2 LiC_D$$

where:

f = carrier frequency - $1.3x10^5$
ω = $2\pi f$
C' = Coupling capacitance of last stage $\approx 4x10^{-12}$ farads
K = Coupling coefficient = 4.5
Li = 200 millihenries
C_D = 100 picofarads

The quantity $1/\omega^2 LiC_D$ is due to the isolation choke Li and terminal capacitance C_D.

Assuming a beam current of $I=10^{-2}$ amperes

$$\Delta E = 167 \text{ volts}$$

The anode supply ripple at very low frequencies is attenuated by the inner-loop. Any remaining ripple that does result in carrier frequency modulation will be attenuated by the filtering action of the terminal capacitance and the effective load. This attenuation factor is $1/1+pC_DR_L$. The measurements show that the ripple voltage does not follow the above relationships since certain assymetries inherent in the end-termination of the last rectifier stage were neglected.

Results of Measurements

The results of ripple measurements are shown in Figure 3a and 3b. The total peak-to-peak ripple at 3 Mev and 5 ma electron beam current is 3900 volts or $\pm$ 0.065 percent of maximum energy. The breakdown of ripple components is shown in Figure 3b. The main component is 120 Hz contributed by the modulation of oscillator tube grids by the a.c. filaments. The next set of measurements, Figure 4a, and 4b, were taken with d.c. filaments on the oscillator tubes. The results are significant in that the total peak-to-peak ripple decreased to 1450 volts or $\pm$ 0.025 percent of maximum energy.

The largest ripple component remaining with d.c. filaments is the 129 KHz oscillator carrier. It is noted from Figure 4b that the r.f. ripple does not change with the beam current and, must be related to assymetry in the high voltage generator layout. Two approaches can be taken here: 1) split the high voltage terminal into two sections so that a double-stage LC filter can be employed, 2) use a moveable plate between the r.f. electrode and the vessel to cause small changes in the voltage on the r.f. electrode in order to balance the induced r.f. voltages on the high voltage terminal. Obviously, both techniques can be used together. It is expected that the high frequency ripple can be reduced to 600 volts peak-to-peak or $\pm$ 0.01 percent of maximum energy. Lower frequency ripple components can be further reduced by higher inner-loop gain and better shielding of amplifiers and signal wires.

Load regulation results are shown in Figure 5a, b and c. Variations in voltage at 1.0 and 2.0 Mev are $\pm$ 0.02 and $\pm$ 0.01 percent respectively. At 3.0 Mv the largest change $\pm$ 0.04 percent is due to the decrease in loop gain. It should also be noted that the percentages are of set voltage and not maximum voltage.

The regulation error due to beam load is minimal and is exceeded by system noise which is due to either amplifier noise or random corona currents on the resistor board. The former may be improved by utilization of a preamplifier with better noise and drift specification, better signal wire shielding, and tighter control of voltage gain over the active control region with the addition of higher loop gain. It appears feasible that $\pm$ 0.01 percent stability can be achieved under load regulation with these added refinements.

The high voltage resistor column which is used for voltage regulation is not an absolute measurement and is subject to small changes in resistance due to aging, temperature changes and corona currents.

The use of a beam slit regulator with an analyzing magnet in conjunction with the voltage regulator is recommended where reproducibility of voltage and long-term stability is required. The voltage regulator makes short-term corrections and the slit regulator takes care of long-term changes in the beam energy.

TABLE I

K_1	Preamplifier gain ≈ 10^4 volts/volt
K_2	Inner-loop amplifier gain = 200 volts/volt
K_3	Tetrode tube gain (VT_1)=70 volts/volt
K_4	Cathode follower driver gain (VT_2) ≈ 1 volt/volt
K_5	Series-pass tubes gain (VT_{3-4}) ≈ 1 volt/volt
K_7	Series regulator feedback gain $R_3/R_5 = 10^{-2}$ volts/volt
K_8	Oscillator transfer function gain = 0.8 V_{rf}/V_{dc}
K_9	R.F. transformer (L) step-up ratio = 38 V_{rf}/V_{rf}
K_{10}	High voltage generator function = 14.2 (1 + IZ/Eo) V_{dc}/V_{rf}
K_{11}	High voltage resistor board function = $50x10^{-12}$ ohm^{-1}
K_{12}	Coaxial cable function = $4x10^5$ volts/amp
K	Coupling coefficient = 4.5
T_1	Time constant of preamplifier feedback = C_1R_2 = 0.168 sec.
T_6	Time constant of stabilization feedback = C_2R_4 = $25x10^{-7}$ sec.
T_7	Time constant of series regulator feedback = C_3R_5 = $1.2x10^{-5}$ sec.
T_2	Time constant of inner-loop amplifier = C_3R_3 = $1.2x10^{-7}$ sec.
T_9	Time constant of tank circuit inductance = $L/2R_e$ = $3.4x10^{-4}$ sec.
T_{10}	High voltage terminal time constant = C_DR_L = 0.6 sec. max.
T_{12}	Coaxial cable response - $C_cR_f=12x10^{-4}$ sec.
R_1	5.6 megohm
R_2	5.6 megohm
R_3	100 K ohm
R_4	50 K ohm
R_5	10 megohm
R_F	400 K ohm
R_L	$6x10^9$ ohms (worse case, resistor boards only)
C_1	0.03 μf
C_2	100 pf
C_3	1.2 pf
C_D	100 pf
L	2.1 millihenries
Li	200 millihenries
n	non-dimensional <1
E	Terminal voltage
E_o	No-load terminal voltage
E_f	Peak r.f. voltage
I	Beam current
Z	Cascade impedance = 24 megohms
N	Number of stages

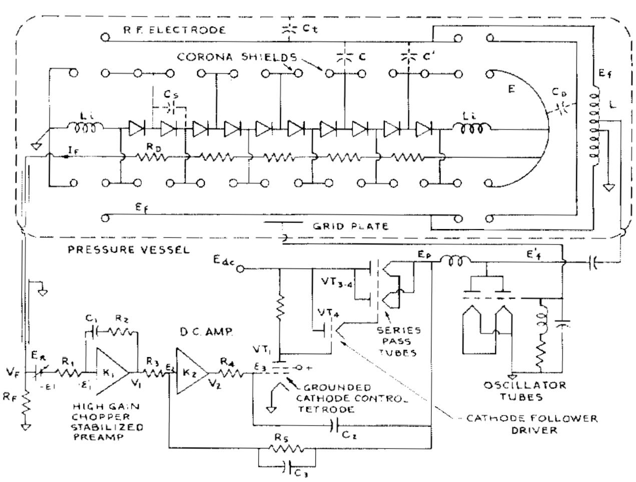

Fig. 1. Schematic—H.V. Generator and Control System.

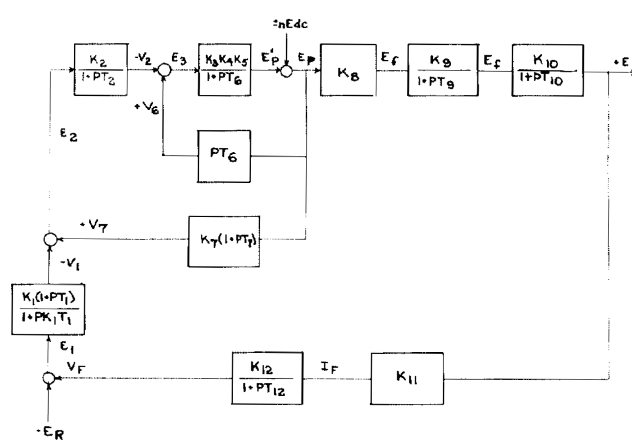

Fig. 2. Block Diagram of the Voltage Regulator.

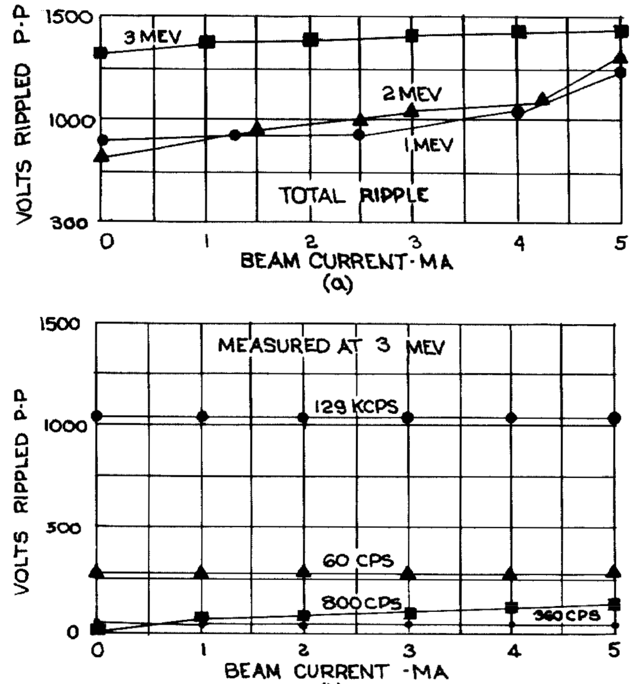

Fig. 4. Ripple Measurements—D.C. Heated Oscillator Tube Filaments.

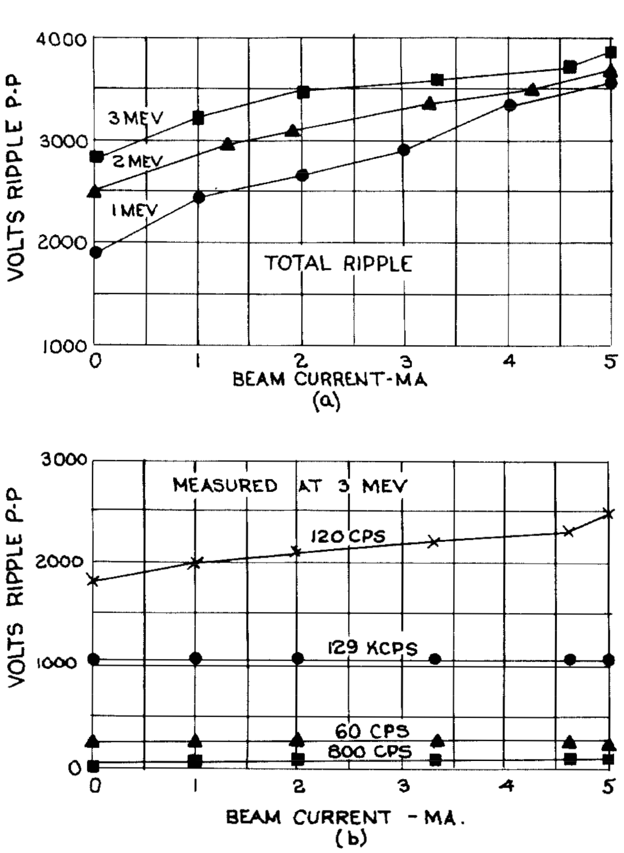

Fig. 3. Ripple Measurements—A.C. Heated Oscillator Tube Filaments.

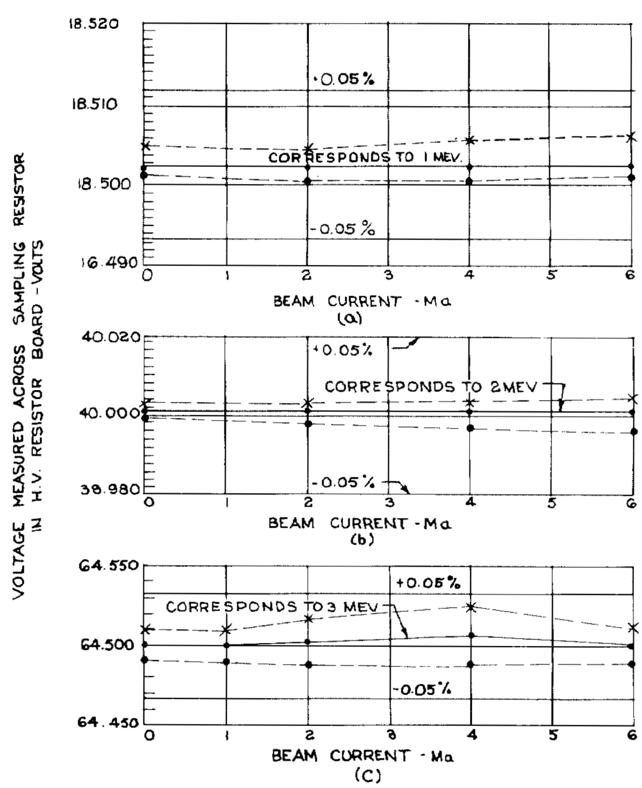

Fig. 5. Beam Load Regulation at 1.0, 2.0, & 3.0 MeV.