June 19, 2001
F: Report no.30

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Evaluation of the Accelerator charging system under a continuously pulsed Electron Beam Load

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1. The Accelerator Charging System

The system is composed of the following subsystems (see Fig. 1):

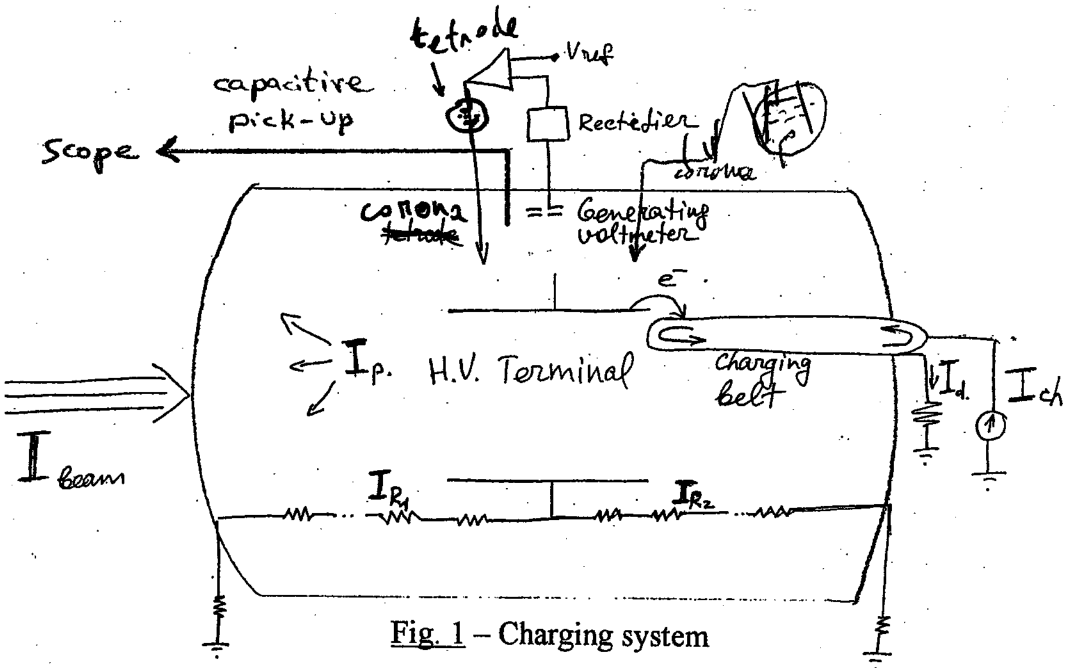


Fig. 1 – Charging system

a. A charging belt rotating at 2Hz frequency. The belt parameters are:
   Width: W = 50 cm
   Length (total) = 12 m
   Speed: v = 24 m/sec
   Maximum charge allowable on belt (according to Jerzy): dQ/dA = 2.65 nC/cm^2.
   Consequently maximum charging current possible by the belt:
   $I_{ch} = (dQ/dA)\cdot W\cdot v = 320\ \mu A$
   The charging current I_{ch} is supplied by a current supply (meter max. current - 1mA). The Down charge I_D (current returned from the terminal upon the belt) is measured on a resistor. In regular operation (V_T = 1.4 MV). The terminal voltage can increase up to 100kV during 0.25sec .

b. Two bleeding resistor chains containing each 70 resistors of 400 MΩ. The total resistance on each side is $R_1 = R_2$ = 28GΩ. The resistor leakage currents I_{R1}, I_{R2} are measured separately for both chains over a load resistance in the control room.

The currents at V = 1.5MV should be:

$I_{R1} = I_{R2} = 53\mu A$

$I_R = I_{R1} + I_{R2} = 106\mu A$

The measurement of I_R is used also to determine V_T.

c. Average (DC) Terminal voltage measurement

Crude measurement of the terminal voltage is made using a "Generator Voltmeter" which is a capacitor with a rotating wing plate. The plate rotates at 50Hz frequency. It measures a voltage proportional to the terminal voltage V_T (related to the ratio between the spacing between the capacitor plates and the distance from the terminal). The generator voltage V_{GV} is rectified and shown on a meter in the control room. Voltage V_R is also measured from I_R ($V_T = I_{R1} \cdot R_1$)

d. Time dependent terminal voltage measurement.

Temporal variation of the terminal voltage can be measured by means of a capacitive peak-up probe described in Append. C (taken from the machine manual book).

The transfer function response of the voltage signal on the oscilloscope $E_2(t)$ to the voltage signal on the terminal $E_1(t)$ is:

$$E_2(s) = T(s)\, E_1(s)$$

$$T(s) = \frac{R_3 C_2 S}{R_3 (C_2 + C_3) S + 1} = \frac{C_2}{C_2 + C_3} \cdot \frac{S}{S + 1/\tau}$$

$$E_1(t) = C_1 \int_0^t i_c(t')\,dt'$$

$$\tau = (C_2 + C_3) R_3$$

For the exemplary parameters given in Append. C.:

$C_2 = 0.3pF$

$C_2 + C_3 = 6nF$

$R_3 = 1M\Omega$

$\tau = 6mS$

At high frequencies:

$2\pi f = s >> 1/\tau$, the transfer function does not distort the signal and just attenuates it by a factor

$$T(S \gg 1/\tau) = \frac{C_2}{C_3}\left(= \frac{1}{20{,}000}\right)$$

At low frequencies T(S) α S and thus $E_2(t)$ α $E_1(t)$.

It seems that in order to see the voltage variations associated with the ~ 10μS beam current pulses one will need to use $R_3 < 1\ k\Omega$.

e. Corona discharge and feedback system

After charging the terminal to a desirable voltage (determined by the parameter I_{CH} only), the active corona discharge system is brought into operation by means of a remote controlled motor pushing the needle. The corona discharge current I_{CD} is controlled by a tetrode. The tetrode current is regulated by a comparator which compares the measured Generator Voltage $\bar{V}_{GV}$ to a reference voltage V_{REF}. The feedback response time is limited by the Generating Voltmeter ac period i/f = 1/50 Hz = 20mS. It is probably more than 50msec since the signal is rectified. If in the future the terminal voltage measurement will be based on the measurement of I_R instead of $\bar{V}_{GV}$, the feedback response time can be made much shorter.

The bias corona current ($\bar{I}_{CD} \cong 10-25\mu A$) determines the dynamic range of voltage regulation since $I_{CD} > 0$ at all times. If the voltage V_T fluctuates down too much till $(I_{CD})_{min} = 0$ or up too much till $(I_{CD})_{max} = 60\mu A$, the corona discharge can not help to bring the voltage back.

2. Current Leakage Balance

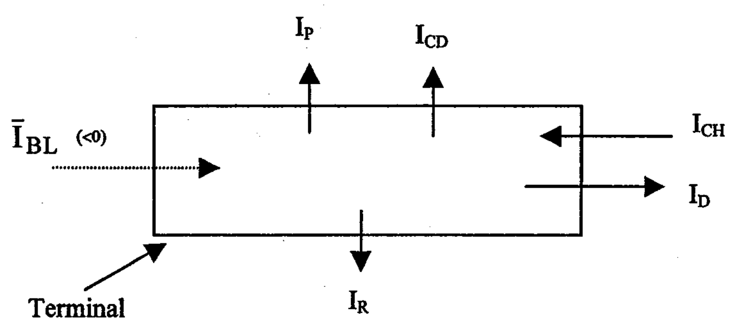


Fig. 2. Diagram of currents flow into and out of the terminal

I_{CH} – Belt charging current
I_D - Down charge (belt return current)
$I_R = I_{R1} + I_{R2}$ – Resistor bleeding current
I_{CD} – Controlled corona current
I_P – Parasitic (uncontrolled) leakage
$\bar{I}_{BL} = -|\bar{I}_{BL}|$ Electron beam leakage current

At steady state:

Without e-beam	$I_{CH} = I_D + I_R + I_{CD} + I_P$
With e-beam	$I_{CH} = I_D + I_R + I_{CD} + I_P + \bar{I}_{BL}$

If the currents do not balance the voltage V_T changes.

In typical operation (without e-beam) at $V_T = 1.5MV$:

$I_R = 120\mu A$, $I_D = 8\mu A$, $I_{CD} = 10\mu A$, $I_{CH} = 220\mu A$

$\Rightarrow I_P \cong 80\mu A$.

The amount of e-beam leakage current that can be allowed at steady state depends on the maximum belt charge current $(I_{CH})_{max}$ that the belt can carry. All the other leakage currents are constant for given V_T.

We have records of M. Kanter from 1998, suggesting that at V_T = 3.5MV a current I_{CH} = 460μA was measured. If we assume that this is $(I_{CH})_{max}$, then the maximum e-beam leakage permissible at steady state is:
I_{BL} = 460-220=240μA.

3. Measurement of $(I_{CH})_{max}$

In order to operate the FEL with a continuous train of e-beam pulses, we must be able to provide the maximum charging current possible to balance the average leakage current from the e-beam.

The following experiments are proposed for measurement of the maximum charging current possible and experimental simulation of the continuous pulse operation:

a. It is possible to establish electrical connection to the terminal without breaking the high gas pressure, pushing a conductor lead from the accelerator wall to the terminal. Operating the belts with maximum current while measuring the current through the shorting lead will give the required $(I_{CH})_{max}$.

b. After conditioning, drop down the terminal voltage to zero, and then start charging with maximal current. The current supply must be switched off quickly before the terminal voltage overshoots and a break-down occurs.

c. Operate the e-gun with low cathode temperature or appropriate grid voltage in order to reduce the e-beam current (e.g. to $\bar{I}_{BL} \cong 100\mu A$); shoot the entire e-beam on the terminal. If starting from steady state, the voltage will drop with τ = RC time constant. This can be monitored on the scope hooked-up to the capacitive peak-up probe. Now I_{CH} can be increased to come back to the steady state voltage V_T. Again $\bar{I}_{BL}$ will be increased and subsequently I_{CH}. When the process cannot be continued further we find $(I_{CH})_{max}$, $|\bar{I}_{BL}|_{max}$.
Because the e-beam current may drop unintentionally, one should consider to arrange automatic switching-off of the charging current-supply to prevent terminal voltage overshoot and subsequent voltage breakdown.

d. Replicate (b) with a train of pulses that will simulate the planned e-beam operation. For example, if the e-gun gate will be driven to produce 2mA 100μS pulses with repetition rate of 50Hz, this will produce an average leakage of 100μA (this experiment simulates operating with a pulsed 1A e-beam of the same pulse train waveform and leakage factor of 0.2%). The terminal voltage response may be measured on the scope connected to the capacitive peak-up probe. It may be also measured possibly with less accuracy and time resolution with an oscilloscope connected in serries to the bleeding resistors.

4. Models and simulations

The characteristics of the system under the conditions of operation with a pulsed electron beam were studied using the "simulink" simulation program (Append. A) and an analytical calculation (Append. B).
The simulink program is a matlab toolbox. The simulation model is based on a simple equivalent circuit comprising the terminal capacitance and the total column resistance R as shown in Fig. 4. The model capacitance is 330 pF. The column resistance *actual* measurement is 11.5 Gohm.

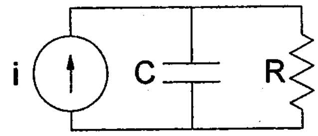


Fig. 4. A simple model of the charging system

The current supplied to the RC circuit is: $I(t) = I_{CH} - I_D - I_{CD} - I_{BL}(t)$ where $I_{BL}(t)$ is the leakage current from the e-beam. The other currents are constant and defined in Sect.2. At steady state $(I)_{avg} = \bar{V}/R$ and the equation reduces to the steady state equation of Sect. 2.

The simulink program simply calculates the voltage over the capacitance V(t) by direct integration of the equation

$$V(t) = \frac{1}{c}\int_0^t \left(I(t') - \frac{V(t')}{R} \right) dt$$

as illustrated in the box diagram of Fig. A1,A3.

The simulations revealed that for parameters of pulse-train operation that were considered (case 1: $T_p = 60\mu s$. $f_{rep} = 400Hz$ and case 2: $T_p = 600\mu s$. $f_{rep} = 40Hz$), the terminal voltage displays a saw-tooth waveform with respective maximum voltage drop of 1.1kV (case 1) and 10.5kV (case 2 – see Fig. A5). This means that in case 2 one should inquire if mode hoping may take place during the lasing pulse.

In both cases the average beam leakage current during the e-beam pulse-train was assumed to be $\bar{I}_{BL} = 144\mu A$. This is a significant current relative to the net charging current at steady state (for V=1.4MV) in the absence of electron beam: $I_R = 120\mu A$. This means that the charging current of the belt when the e-beam is on, should be increased by $\bar{I}_{BL} = 144\mu A$, or for the example of Sect. 2.
$I_{CH}(t > t_0) = 220\mu A + 144\mu A = 364\mu A$.

It should be noticed that if the belt charging current remains ON and the e-beam leakage current turns OFF from steady state operation at any time $t = t_1$, the terminal voltage will start rising from the steady state voltage
($\bar{V}(t \langle t_1) = R \cdot I(t \langle t_1) = 1.5 Gohm$ x $120\mu A = 1.4MV$) to a new steady state voltage
($\bar{V}(t \rangle t_1) = 11.5 Gohm$ x $(120+144)\mu A = 3.06MV$) within a rise-time of RC-$t_0 \cong 1.5$sec. <u>This is a point of concern</u>, because such a situation is likely to produce a voltage breakdown.

This problem will arise primarily when one turns off the e-gun either intentionally or accidentally. The belt charging current, should always be turned off before turning off the beam current. To avoid a breakdown due to accidental turning off of the e-beam it is recommended to install an emergency switch that will turn off the belt charging current when the terminal voltage starts going up.

A limiting factor to this remedy is the response time of the charging system. As discussed in Sect. 1, the limiting factor is probably the time in which the belt makes half a cycle and carries the new charge to the terminal ($\tau \cong 0.25$Sec). Simulink simulation showed that during this time the terminal voltage will rise by $\Delta V = 100$kV. This may be a tolerable voltage rise if the emergency switch starts having effect from this point on.

Appendix A:

The simulink program is a Matlab toolbox. The integration program was stored in files model 6.mdl (or model7.mdl).

We ran the simulation for two cases in which the current pulse generator produces a square-wave pulse train with pulse duration T_p, repetition period T_{rep}, pulse current I_B and Duty Cycle factor (D.C.). The constant current sources are turned on at t = o, the pulse generator is turned on at $t = t_0$ (=2.3343 sec) which is exactly the time at which the terminal arrives to the accelerator steady state operating voltage during pulse-train operation ($\bar{V} = 1.4MeV$). The time t_0 was calculated from :

$$\bar{V} = RI(t\langle t_0)\left(1 - e^{-\frac{t_0}{RC}}\right)$$

In order that the terminal voltage will keep the same average value V after $t = t_0$, the D.C. factor must be adjusted to keep the steady state relation

$$\bar{I}(t\rangle t_0) = I(t\langle t_0) + \bar{I}_{BL} = I(t\langle t_0) + I_{BL} x D.C. = \frac{\bar{V}}{R}$$

Case 1: (Fig. A1, A2)

e-beam leakage current amplitude	I_{BL} = 6mA
Duty cycle	D.C. = 2.4 %
Repetition period	T_{rep} = 2.5mS (f_{rep} = 400Hz)
Pulse duration	T_p = 60μS
Average e-beam leakage current	$\bar{I}_{BL} = I_{BL}$ x D.C. = 144μA

This leakage current, keeps steady state operation near $\bar{V} = 1.4MV$. The voltage wave-form at $t > t_0$ is a saw-tooth waveform, which after enlargement of the horizontal curve in Fig. A2 reveals a maximum drop of ΔV = 1.1kV due to terminal discharge during the e-beam current pulse.

Case 2: (Fig. A3, A4, A5)

Keeping the same average leakage current $\bar{I}_{BL}$,

I_{BL} = 6mA
D.C. = 2.4 %
T_{rep} = 25mS (f_{rep} = 40Hz)
T_p = 600μS
$\bar{I}_{BL} = I_B$ x D.C. = 144μA

In this case the maximum terminal voltage drop is ΔV = 10.5kV (see Fig. A5).

Appendix A:

Simulink model and simulations of accelerator charging sequence

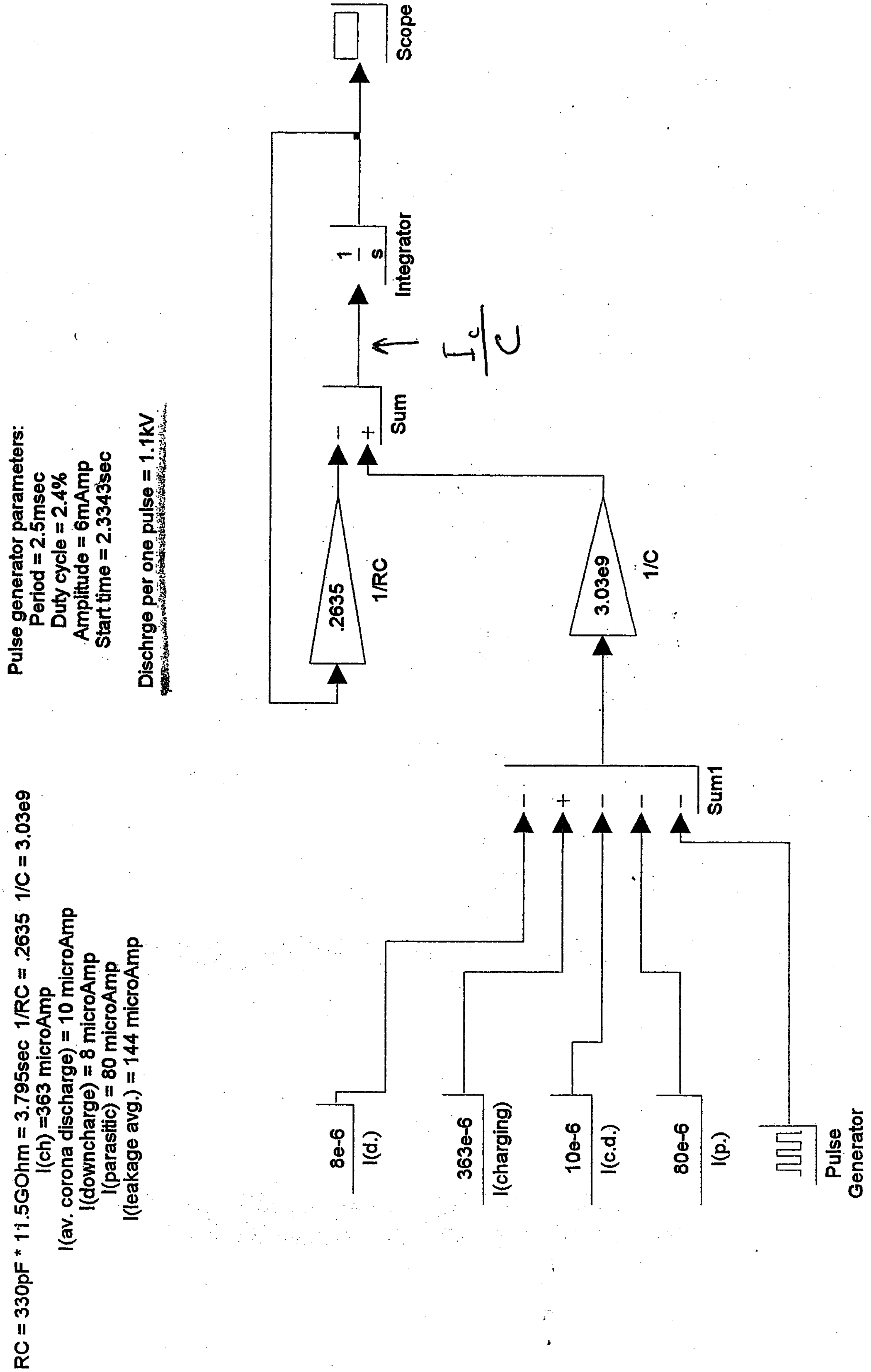
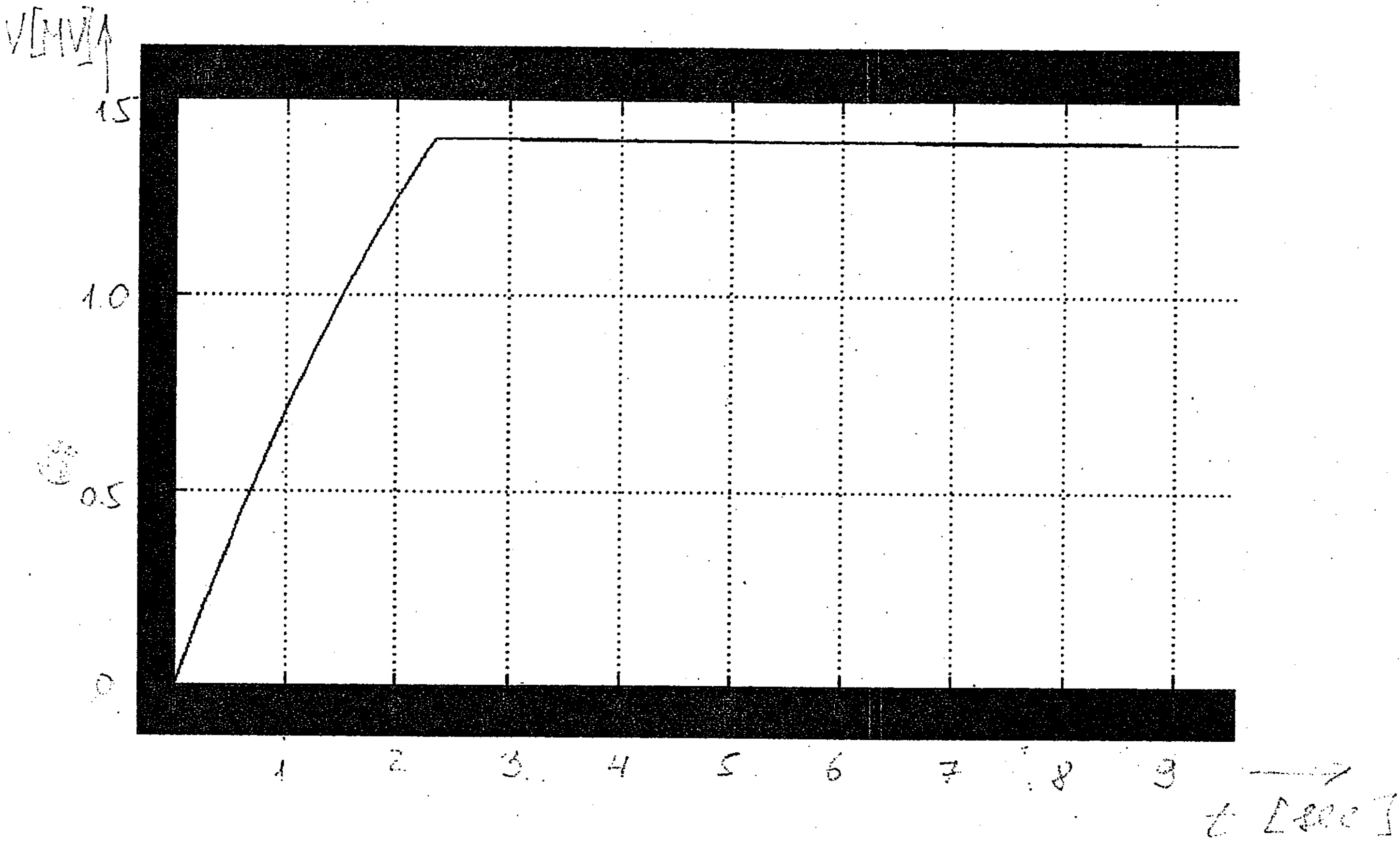


Fig. A1

Graph of terminal potential, while pulses begin at V (teminal) = 1.4 MV
Period = 2.5msec   I(ch.) = 363microAmp
Duty cycle = 2.4%   I(lik.) = 144microAmp
Amplitude = 6mAmp
Start time = 2.3343sec

Dischrge per one pulse = 1.1kV



File:
pulse 2.5ms.bmp
use with: model6.mdl

Fig. A2

RC = 330pF * 11.5GOhm = 3.795sec 1/RC = .2635 1/C = 3.03e9
I(ch) =363 microAmp
I(av. corona discharge) = 10 microAmp
I(downcharge) = 8 microAmp
I(parasitic) = 80 microAmp
I(leakage avg.) = 144 microAmp

Pulse generator parameters:
Period = 25msec
Duty cycle = 2.4%
Amplitude = 6mAmp
Start time = 2.3343sec

Dischrge per one pulse = 10.5kV

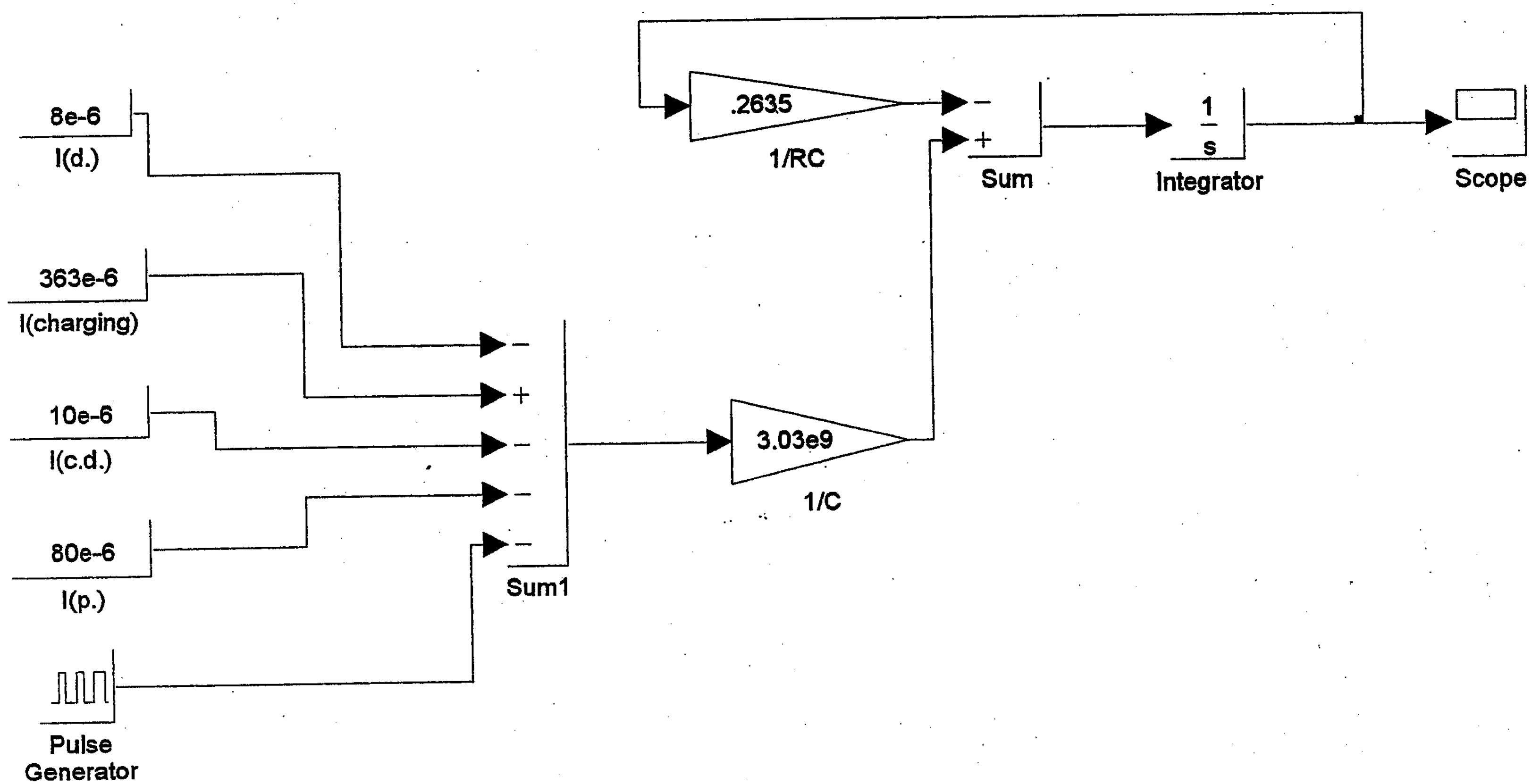
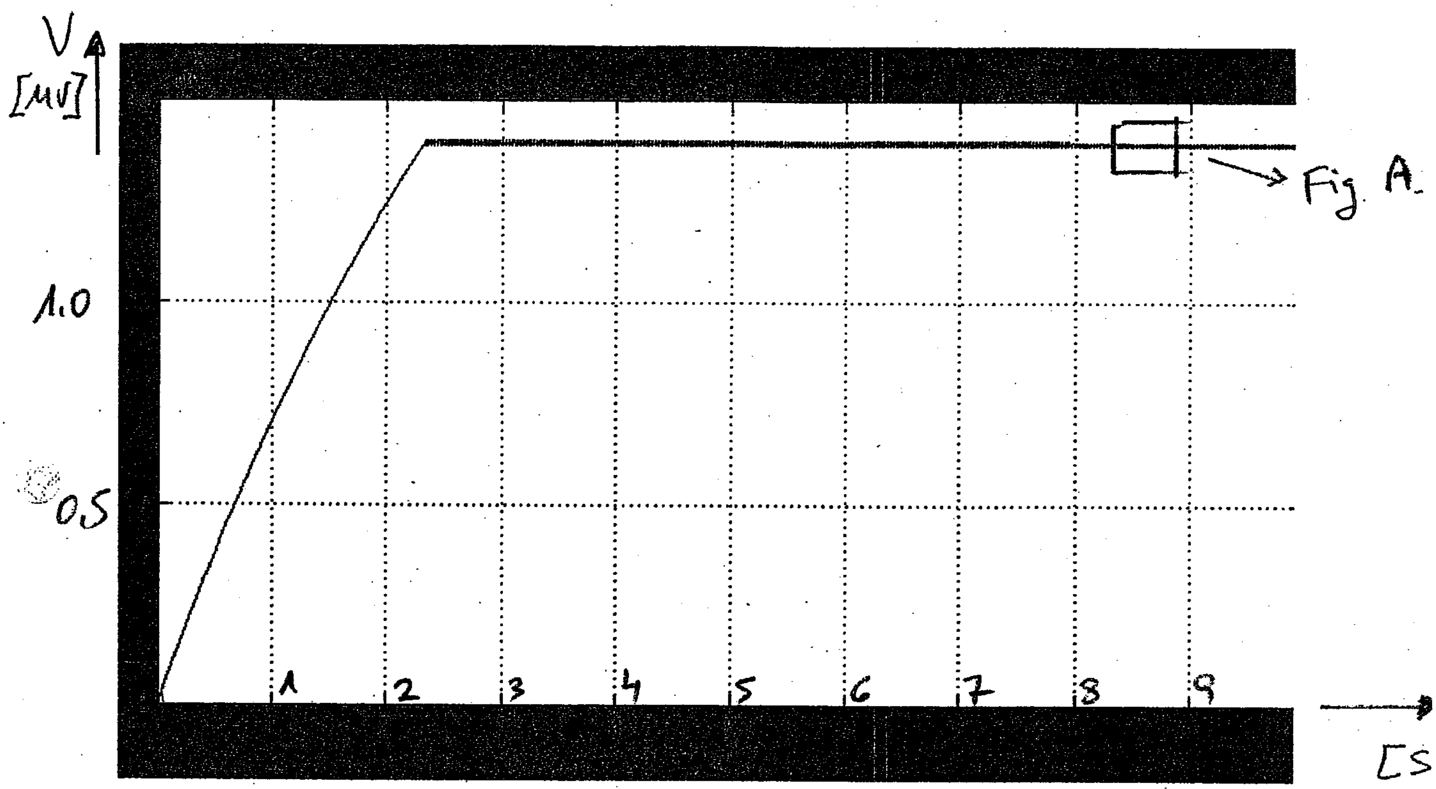


Fig. A3

file : model7.mdl

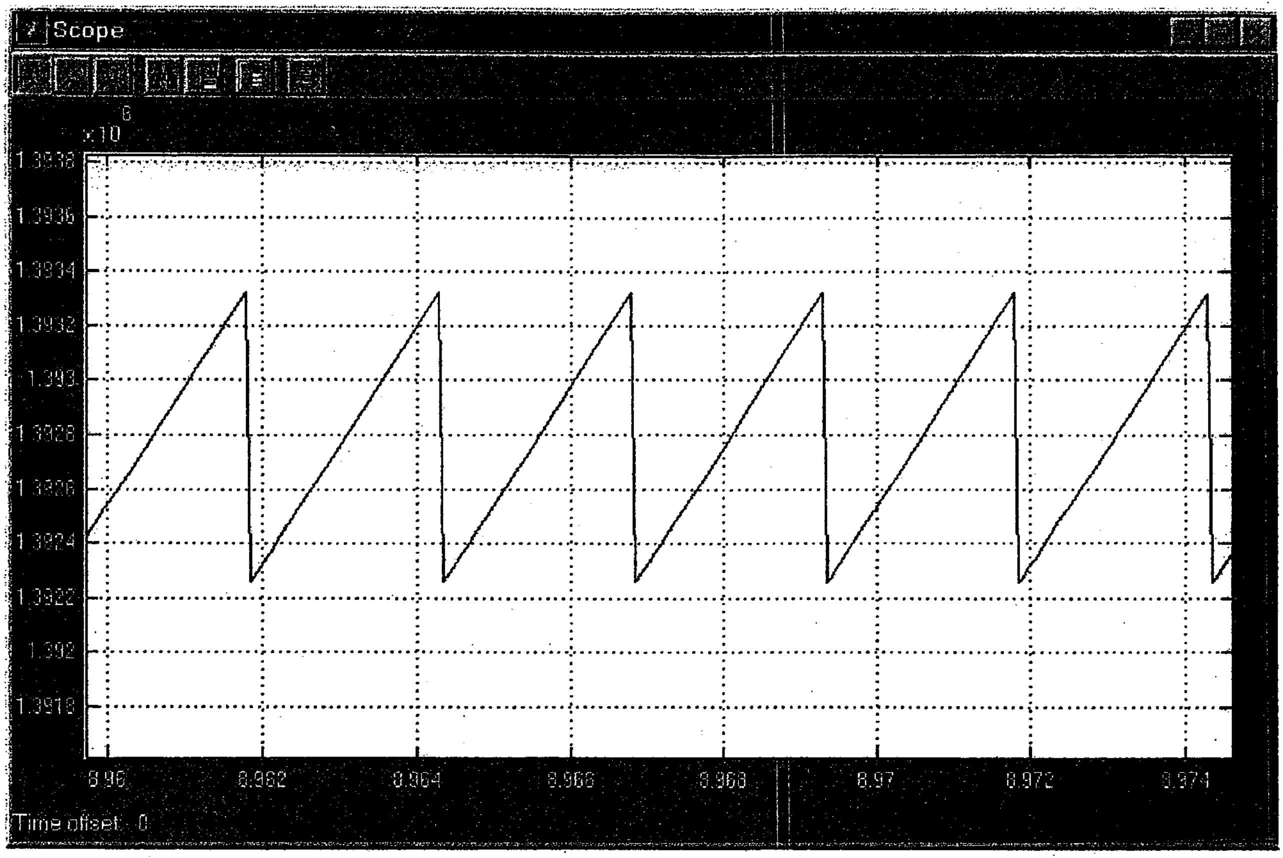
Graph of terminal potential, while pulses begin at V (teminal) = 1.4 MV
Period =25msec I(ch.) = 363microAmp
Duty cycle = 2.4% I(lik.) = 144microAmp
Amplitude = 6mAmp
Start time = 2.3343sec

Dischrge per one pulse = 10.5kV



File: pulse 25ms. bmp
use with: model 7. mdl

Fig. A4



$\tau_{Per} = 25$ msec

Fig. A5

Appendix B:

Analytic solution of accelerator voltage and current waveforms at operation with a continuous train of e-beam pulses

The equivalent circuit of the HV-terminal and the bleeding resistors is

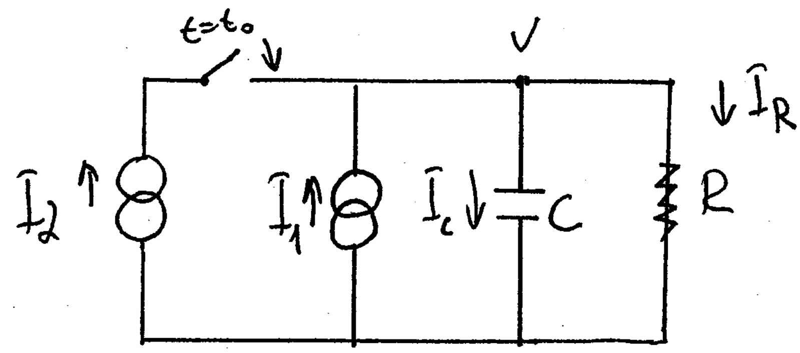


Fig. B1

This circuit models the charging process in three stages:

1. Charging stage.
   Here $I_1 = 0$ and $I_2 = I_{ch}$

2. E-beam pulse duration:
   Here $I_1 = I_{ch}$ and $I_2 = -I_{BL}$. The e-beam leakage current is regarded as a negative (discharging) current source switch on when the e-beam starts. The capacitance initial current I_c drops abruptly by $-I_{BL}$ (while the voltage stays continuous).

3. Recharging period (between e-beam pulses)
   Here $I_1 = I_{ch} - I_{BL}$ and $I_2 = +I_{BL}$. Switching off the beam is equivalent to switching on back I_{ch}. There is an abrupt jump by I_{BL} in the collector current I_C (the voltage keeps continuous).

   The solution of the generic circuit is found from:

   $t > t_0$

$$I_1 + I_2 = I_c + I_R$$

$$I_C = C\frac{dv}{dt}$$

$$I_R = \frac{V}{R}$$

$$\Rightarrow$$

$$I_1 + I_2 = C\frac{dv}{dt} + \frac{V}{R}$$

The solution

$$V(t) = \left[V(t_0) - (I_1 + I_2)R\right]e^{-\frac{t-t_0}{\tau}} + (I_1 + I_2)R$$

$$I_c(t) = \left[I_1 + I_2 - \frac{V(t)}{R}\right]e^{-\frac{t-t_0}{\tau}}$$

Where $\tau = RC$ satisfies proper boundary conditions at $t = t_0$ and $t = \infty$.

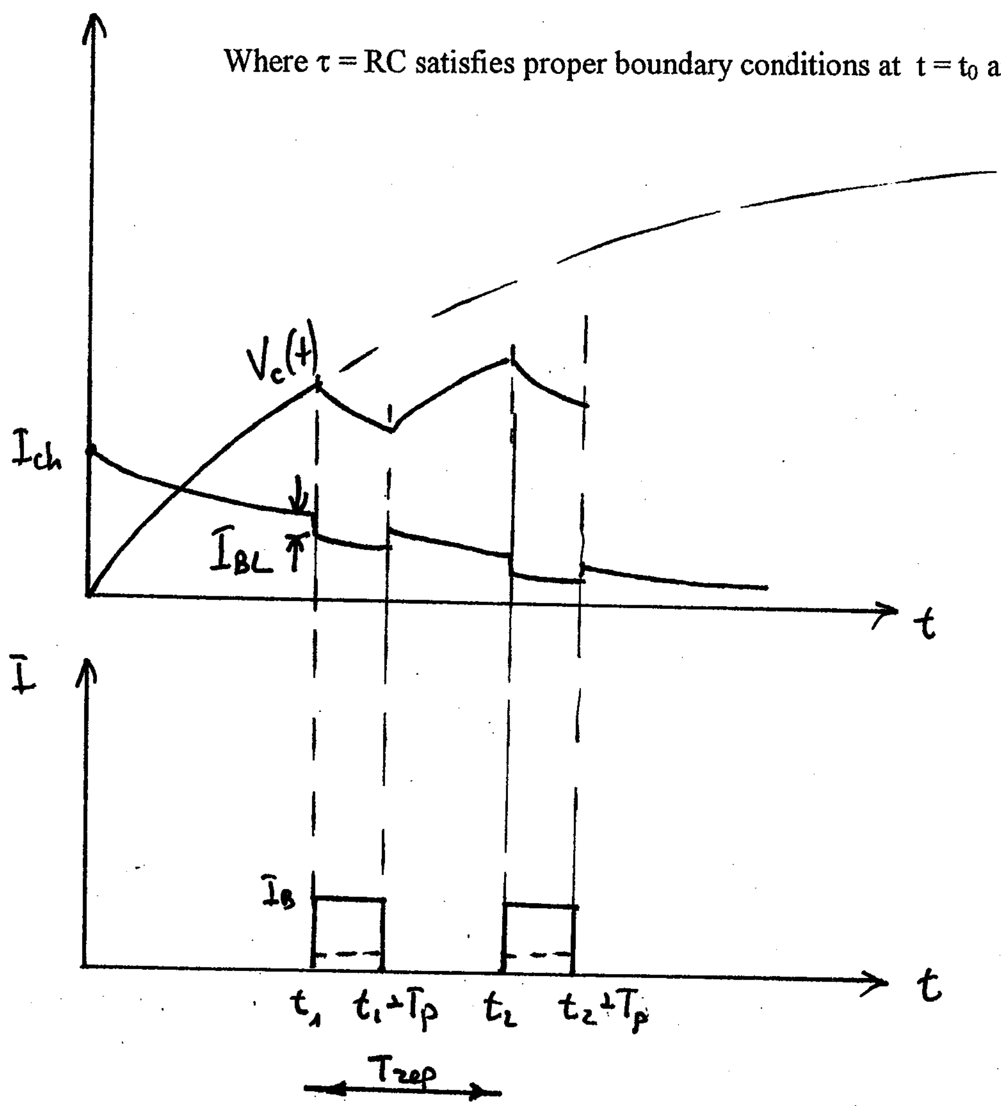


Fig. B2

Applying this solution to the case of a pulse train:

$0 < t < t_1$

$$V(t) = I_{ch}R\left(1 - e^{-t/\tau}\right)$$

$$I_c(t) = I_{ch}e^{-t/\tau}$$

$\underline{t_n < t < t_n + T_p}$

$$V_n(t) = \left[V_n(t_n) - (I_{ch} - I_{BL})R\right]e^{-\frac{t-t_n}{\tau}} + (I_{ch} - I_{BL})R$$

$$I_n(t) = \left[I_{ch} - I_{BL} - V_n(t_n)/R\right]e^{-\frac{t-t_n}{\tau}}$$

$$V_n(t_n) = V_{n-1}(t_n) = V_{n-1}(t_{n-1} + T_{rep})$$

$\underline{t_n + T_p < t < t_n + T_{rep} = t_{n+1}}$

$$V_n(t) = \left[V_n(t_n + T_p) - I_{ch}R\right]e^{-\frac{t-(t_n+T_p)}{\tau}} + I_{ch}R$$

$$I_n(t) = \left[I_{ch} - V_n(t_n + T_p)/R\right]e^{-\frac{t-(t_n+T_p)}{\tau}}$$

When steady state is attained

$$V_n(t_n + T_{rep}) = V_n(t_n)$$

Substitution leads to:

$$V_n(t_n) = \frac{I_{ch}\left(e^{T_{rep}/\tau} - 1\right) - I_{BL}\left(e^{T_p/\tau} - 1\right)}{e^{T_{rep}/\tau} - 1}$$

Solving for I_{ch}

$$I_{ch} = \frac{V_n(t_n)}{R} + I_{BL}\frac{e^{T_p/\tau} - 1}{e^{T_{rep}/\tau} - 1}$$

For $T_p \ll \tau$, $T_{rep} \ll \tau$

$$I_{ch} = \frac{V_n(t_n)}{R} + I_{BL}\frac{T_P}{T_{rep}} = \frac{V_n(t_n)}{R} + \bar{I}_{BL}$$

As assumed earlier

Append C:

INSTRUCTION SHEET
HVI-1016

STABILITY MEASUREMENT BY CAPACITIVE PICKUP

INTRODUCTION

Electrostatic accelerator stability may be determined by capacitive sending of the terminal potential fluctuations. The equipment required and appropriate calculations are detailed.

DESCRIPTION

See Fig. 1 which indicates schematically the equipment used and Fig. 2, the equivalent circuit diagram. The terminal-to-tank capacitance C_1 has across it a potential E. We are concerned only with the fluctuating component of E which arises from the fluctuating component in the current 'i' supplied to the terminal. This fluctuating component of current arises from the cyclic (belt frequency) and random variations in charge by the belt onto the terminal. Other causes can also exist in accelerators which have not been properly conditioned.

A pickup plate insulated from the tank wall senses the changes in electric field due to fluctuations in terminal potential. The fluctuations are displayed on a cathode-ray oscilloscope. To preserve an accurate representation of terminal voltage fluctuations, a level response down to relatively low frequencies is required of the coupling and amplifier input circuit. Because the coupling capacitance (C_2) between the terminal and the pickup plate is very small (in the order of 0.30 μμfd), good frequency response is preserved by using a capacitive potentiometer together with a high-input resistance to the cathode-ray oscilloscope amplifier. The padding capacitance (C_3), consisting of the shielded lead between pickup plate and amplifier together with additional parallel capacitance, must present a relatively low impedance compared with the amplifier input resistance over the frequency range required. Some compromise must be made to accommodate the sensitivity of the cathode-ray oscilloscope. Adequate results are obtained with a total input capacitance of 6000 μμfd (including lead capacitance), an input resistance of 1 megohm, and an oscilloscope sensitivity of 10 millivolts per centimeter. Using these figures and an approximate value of 0.030 μμfd for the pickup capacitance, the attenuation by the capacitive potentiometer is

$$\frac{6,000}{0.30} = 20,000.$$

One centimeter deflection at the oscilloscope corresponds to a 200-volt change in terminal potential.

In a particular test, the actual attenuation and frequency response must be determined by applying a known ac signal to the terminal. A low frequency signal generator having an rms output of 50 volts (140 volts peak to peak) can be used if the oscilloscope sensitivity approaches 1 millivolt per centimeter. The accelerator can be at atmospheric pressure when this calibration is done. Contact is made with the terminal through the corona-stabilizer port with the corona stabilizer removed.

Better low-frequency response is obtained with higher amplifier input resistance (10 megohms), particularly if this is coupled with higher sensitivity.

One problem encountered in these measurements is that of external signal 'pickup' at the higher amplifier sensitivity settings. For this reason the screened coaxial lead from the capacitive probe (or stator plates of the stationary generator voltmeter) should preferably be a continuous run and well-removed from power lines. Exposed signal connections at the pickup point and oscilloscope must be kept short. Only one ground at the tank wall can be used.

The oscilloscope amplifier used in these measurements should have a low-frequency response at least equal to the input circuit-- preferably better. The high-frequency response need be no better than a maximum of 10,000 cps. Even 1,000 cps is acceptable.

Photographic reproductions of the oscilloscope traces can assist the analysis of the accelerator performance and serve as records for customer acceptance of the equipment. The following tabulations indicate the equipment required and results obtained.

EQUIPMENT REQUIRED

1. Pickup Plate --an insulated 'mushroom'.

2. Coaxial Lead --Convenient length 50 feet or more depending on nature of installation. The lead should be one continuous length and the capacity should be known (or measured).

3. Padding Capacitor – About 5,000 µµfd in order to raise total input capacitance including the coaxial lead to about 6,000 uufd (±20% tolerance Adequate).

4. Oscilloscope with Amplifier

Input Resistance	1 megohm minimum
Sensitivity	10 millivolt/cm (1 millivolt/cm preferred).
Frequency Response	Flat over the range 10 cps to 1,000 cps (wider frequency response is preferred)
Sweep Rate	100 milliseconds/cm

5. Low Frequency Signal Generator (for calibration).

Minimum Range	5 cps -- 100 cps
Available Output Signal	At least 50 volts rms

In the absence of such a signal generator, a line voltage signal through an isolating transformer may be used and the frequency response calculated from the known input circuit.

6. Contactor -- Any conductor sufficiently stiff to reach through a tank port and touch (not scratch) the terminal must be insulated from ground and connected to the signal output from the signal generator or isolation transformer.

7. Camera -- Land - Polaroid type preferred - adapted for use with the available oscilloscope.

COMMENTS ON TYPICAL RESULTS

It will be noted that the data taken with the higher (10 megohm) input resistance amplifier more faithfully reflects the terminal excursions. More accurate reproduction can be obtained in the case of the lower (1 megohm) input resistance amplifier provided sufficient (one millivolt centimeter or better) is available to enable a resistance attenuator across the attenuator capacitance to be used. Fig. 3 shows a suitable circuit.

Because this additional resistance attenuator will increase the overall attenuation to about 6×10^6 (R_3a is 9 megohms, C=1,2000 µµfd, R_3b=1 megohm) it will be generally impossible to calibrate with the additional attenuator in place. In such a case the additional attenuator must be removed and calibration carried out at some frequency within the level response characteristic of the input circuit C_3, R_3b.

Equivalent results could be obtained by merely increasing C3, but two accurately known capacitors would be necessary to carry out calibration and accelerator test. Figure 3 requires only one accurately known resistor (R_3a), which can be shorted for calibration.

END

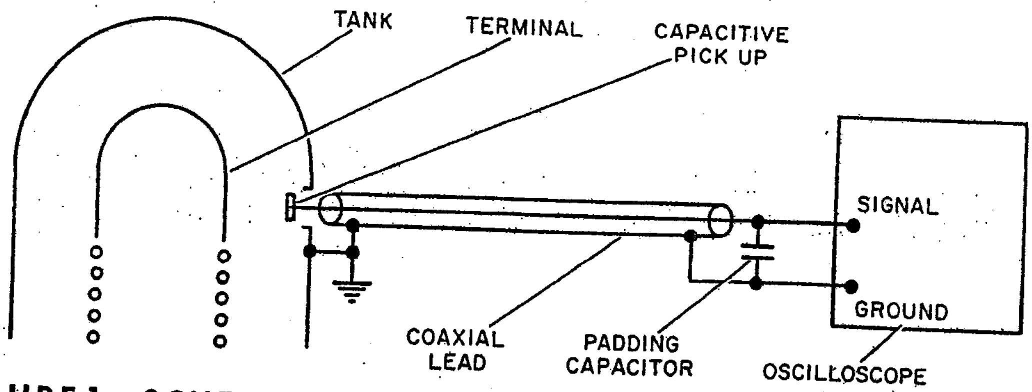
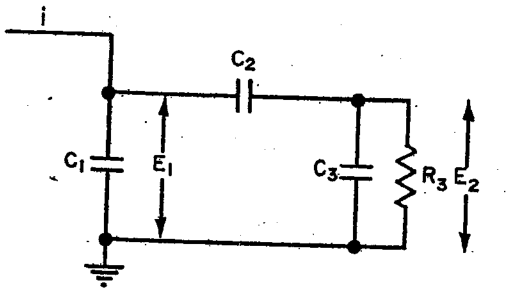


FIGURE 1. SCHEMATIC DIAGRAM FOR STABILITY MEASUREMENT BY CAPACITIVE PICK-UP

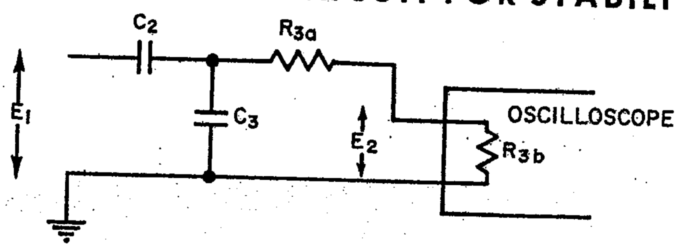


$$E_1 = C_1 \int i\, dt$$

$$E_2 = \frac{C_2}{\left[(C_2 + C_3)^2 + \dfrac{1}{4\pi^2 f^2 (R\ )^2}\right]^{1/2}} \cdot E_1$$

- i — FLUCTUATING CHARGE CURRENT TO TERMINAL
- C_1 — TERMINAL TO TANK CAPACITANCE
- C_2 — TERMINAL TO PICK-UP CAPACITANCE
- C_3 — OSCILLOSCOPE INPUT CAPACITANCE (INCLUDING COAXIAL LEAD AND PADDING CAPACITY)
- R_3 — OSCILLOSCOPE INPUT RESISTANCE

FIGURE 2. THE EQUIVALENT CIRCUIT FOR STABILITY MEASUREMENT



$$E_2 = \frac{R_{3b}}{R_{3a} + R_{3b}} \cdot \frac{C_2}{\left[(C_{3a} + C_3)^2 + \dfrac{1}{4\pi^2 f^2 (R_{3a} + R_{3b})^2}\right]^{1/2}} \cdot E_1$$

FIGURE 3. MODIFIED INPUT CIRCUIT TO IMPROVE FREQUENCY RESPONSE OF LOW INPUT RESISTANCE AMPLIFIER