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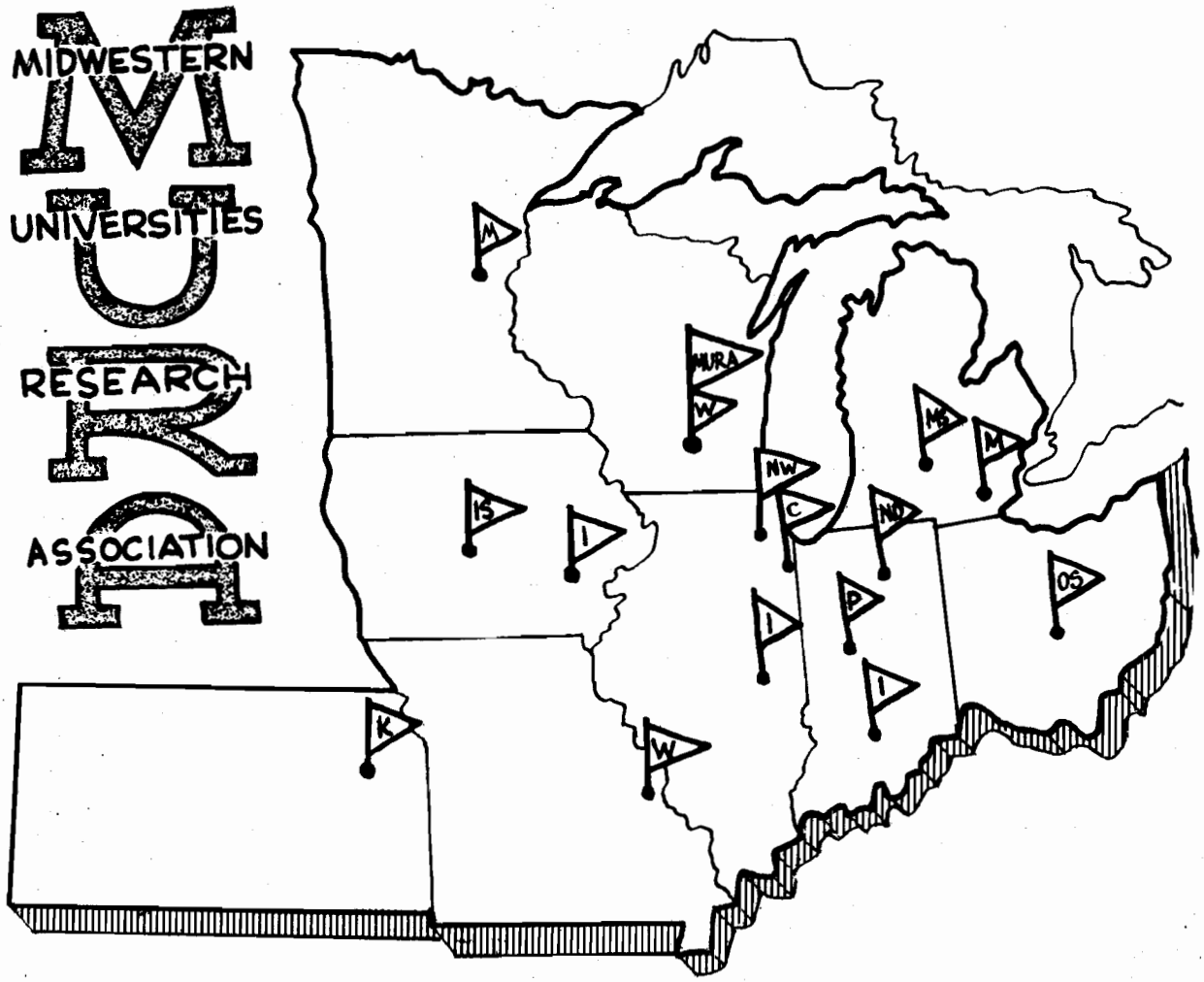

RF PROGRAM FOR THE 40 MEV TWO-WAY ELECTRON MODEL

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RF PROGRAM FOR THE 40 MEV TWO-WAY ELECTRON MODEL

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ABSTRACT

The characteristics of the rf system for the 40 Mev two-way electron model are given. Two possible modes of operation, along with parameters pertinent to each mode, are discussed. The scattering of the stacked beam by rf buckets is treated in Section V. Fig. 5 presents a graph of the energy, frequency, gap voltage, bucket area, effective radius of electron orbit, phase oscillation frequency and stable phase angle as a function of time for one of the modes of operation.

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**University of Minnesota

I. SUMMARY OF CHARACTERISTICS

Number of Cavities: Two; one for accelerating increments of beam to the stack and the other to be a displacement oscillator to replace energy lost by the stacked beam to synchrotron radiation.

Nature of Cavities: Sheet aluminum, air-filled, fixed tune, low Q.

Frequency Range: Accelerating oscillator, 29.48 to 22.94 megacycles/second; displacement oscillator, 22.91 to 23.08 megacycles/second.

Frequency Stability: ± .0087% at the electron pickup frequency of 29.48 megacycles/second. Frequency stability is much less critical at other parts of cycle.

RF Power Generation: Frequency modulated master oscillator followed by an untuned, broad-band power amplifier.

Cavity Voltage: A maximum peak voltage of 500 volts for both cavities.

Peak RF Power to Cavity: A maximum of 10 KVA.

Allowable Energy Spread of Betatron Accelerated Beam: ± 13 kilovolts.

Stability of Betatron Energy: ± 3 kilovolts.

II. MODE OF OPERATION

It is planned that the model will have several possible modes of operation, among which are one-way and two-way beam operation. In the category of two-way beam operation are two particular modes of operation which place certain requirements on the model and its associated equipment. They are:

A. Simultaneous acceleration of a clockwise and a counterclockwise increment of beam from 2 Mev to a two-way stacked beam at 40 Mev at a repetition rate of 60 cycles per second.

B. Alternate acceleration of clockwise and counterclockwise increments of beam from 2 Mev to their respective stacked beams at 40 Mev. A complete cycle consisting of a bucket of beam to both stacked beams will require 1/60 second.

III. SEQUENCE OF EVENTS IN CYCLE

For mode A operation (described in Section IIA), the following events occur in order. See Fig. 1 for a graph of the frequency program.

1. A period of 3 milliseconds is available for the injection and betatron acceleration of clockwise and counterclockwise electrons to an energy of 2 Mev. This may be accomplished by double pulsing the betatron as shown in Fig. 1 and injecting 100 Kv electrons in opposite directions at the times shown.
2. The accelerating oscillator turns on at peak voltage of 15 volts and a frequency of 29.48 megacycles/second to capture the 2 Mev electrons.
3. The rf voltage rises adiabatically to 250 volts, while the frequency modulation gradually begins.
4. Main acceleration occurs. During this period, the displacement oscillator is turned on and modulated down through the stacked beams four times in order to restore to both stacked beams the energy lost by synchrotron radiation in 1/60 second.
5. The rf voltage is lowered adiabatically to 225 volts as the stacking region (38-40 Mev) is approached.
6. The rf voltage is maintained at 225 volts while passing through the stack.

7. The rf voltage is abruptly turned off when the frequency reaches 22.94 megacycles/second. This completes the cycle. The sequence requires 1/60 second.

For mode B operation (described in Section IIB), the following events occur in order. See Fig. 2 for a graph of the frequency program.

1. A period of 2 milliseconds is available for the injection and betatron acceleration of clockwise electrons to an energy of 2 Mev.
2. The accelerating oscillator turns on at a peak voltage of 15 volts and a frequency of 29.48 megacycles/second to capture the 2 Mev electrons.
3. The rf voltage rises adiabatically to 500 volts, while the frequency modulation gradually begins.
4. Main acceleration occurs. During this period, the displacement oscillator is turned on and modulated down through the stacked beam twice in order to restore to both stacked beams the energy lost by synchrotron radiation in 1/120 second.
5. The rf voltage is lowered adiabatically to 421 volts as the stacking region (38-40 Mev) is approached.
6. The rf voltage is maintained at 421 volts while passing through the stack.
7. The rf voltage is abruptly turned off when the frequency reaches 22.94 megacycles/second.
8. Electrons are injected counterclockwise and betatron accelerated to an energy of 2 Mev in a period of 2 milliseconds.

Following Step 8, Steps 2 through 7 are repeated thus completing the acceleration of an increment to both stacked beams at 40 Mev. The entire sequence requires 1/60 second.

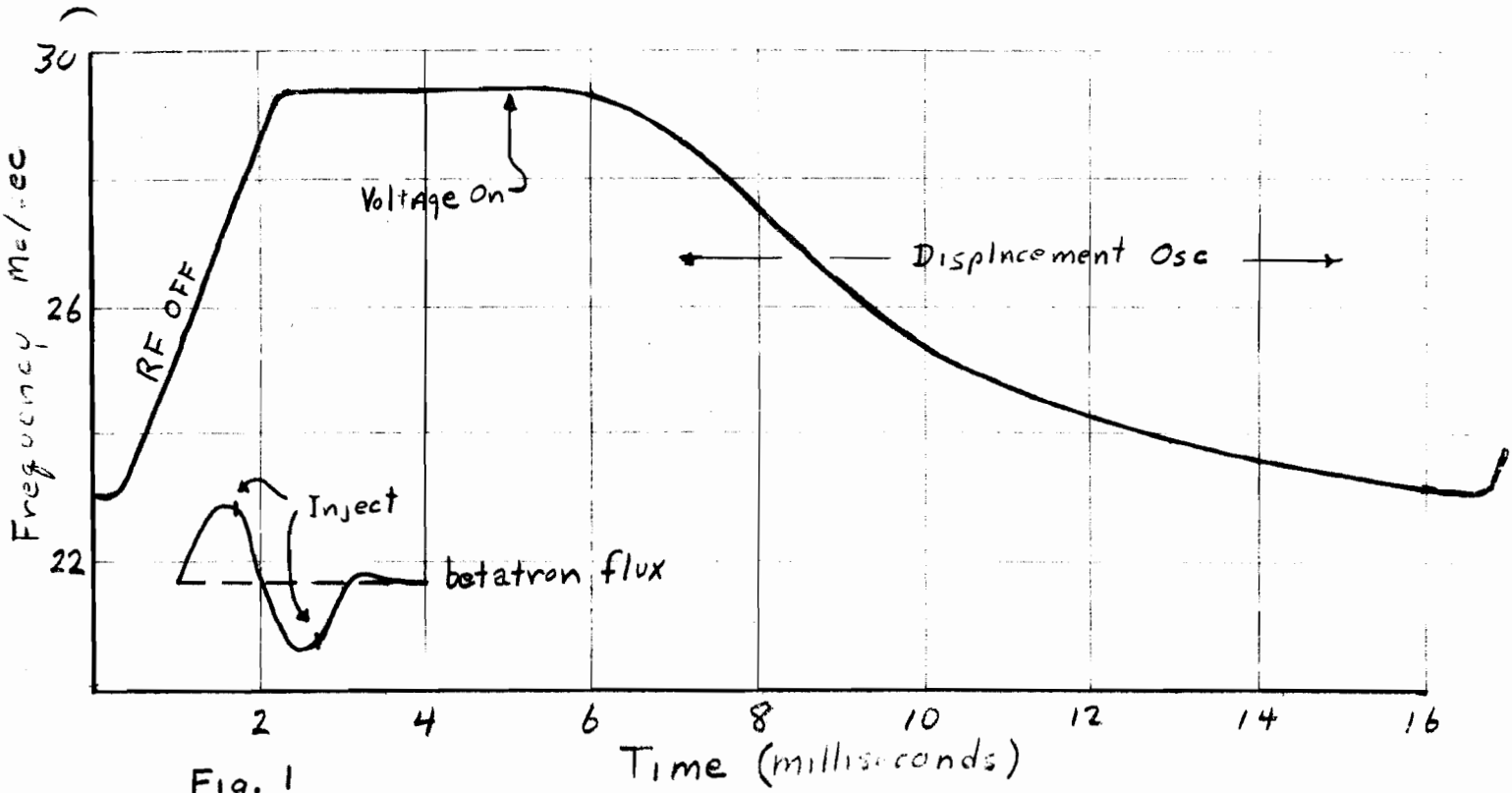
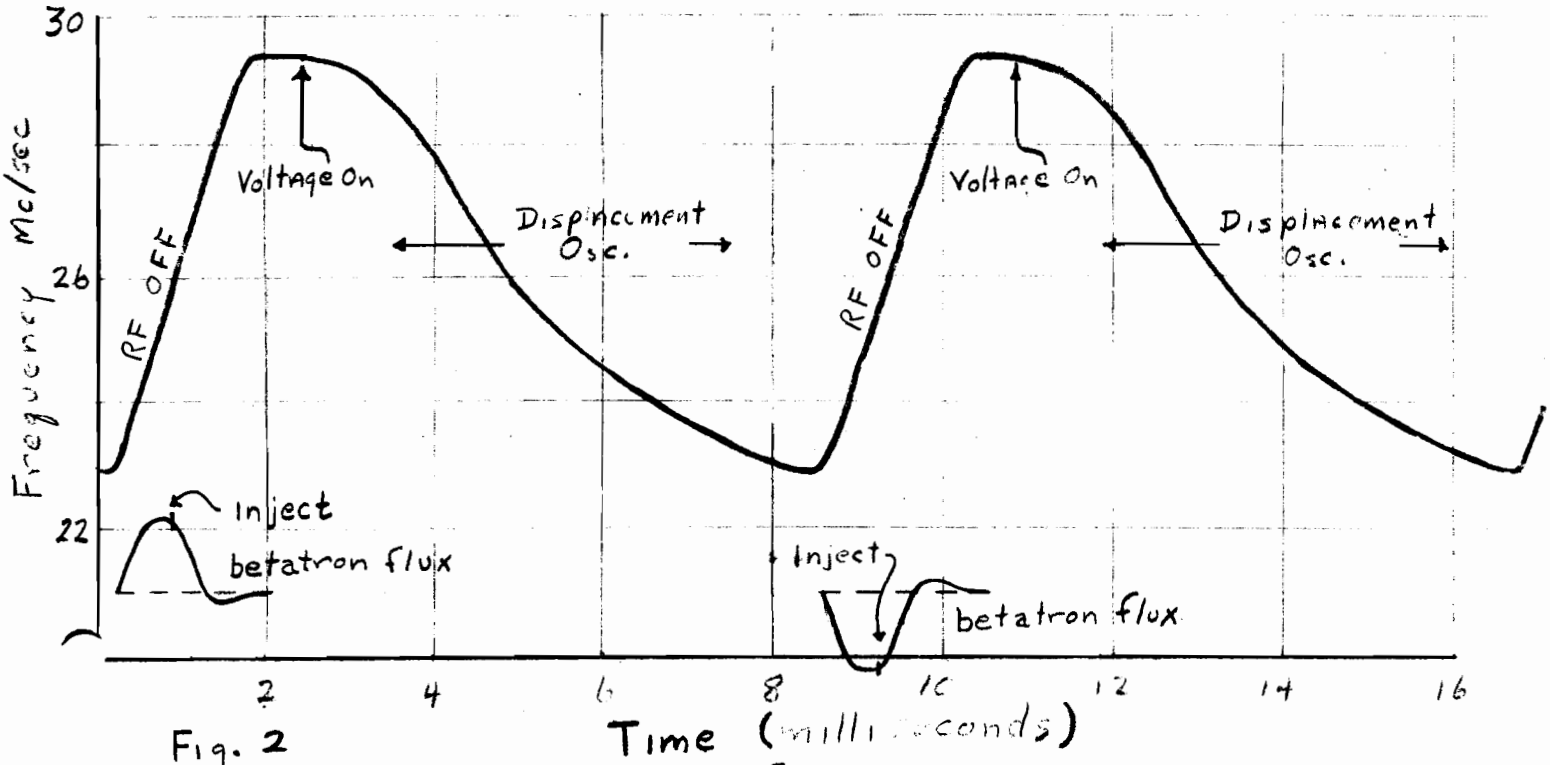

30
26
22
Frequency Mc/sec
RF OFF
Voltage On
Displacement Osc
Inject
betatron flux
2
4
6
8
10
12
14
16
Time (milliseconds)

Fig. 1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Frequency Mc/sec
RF OFF
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Displacement Osc.
Inject
betatron flux
RF OFF
Voltage On
Displacement Osc.
Inject
betatron flux
2
4
6
8
10
12
14
16
Time (milliseconds)

Fig. 2

IV. CONSIDERATIONS LEADING TO PARAMETERS

The gap voltage V, for this model (and hence the repetition rate), is limited by the requirement that the rf bucket parameters must be changed adiabatically during the acceleration cycle. An adiabatic change is defined as a change which occurs slowly with respect to the phase oscillation frequency.

For a given stable phase angle ϕ_s, the phase oscillation frequency varies as $V^{\frac{1}{2}}$ and the time required for acceleration to the final energy varies inversely as V. Increasing the stable phase angle decreases the phase oscillation frequency and increases the repetition rate.

For mode A operation, a gap voltage of 250 volts, and a stable phase angle of 43°, is sufficient to give the required repetition rate of 60 cycles per second and approximately 110 phase oscillations per cycle.

For mode B operation, a gap voltage of 500 volts, and a stable phase angle of 43°, gives a repetition rate of at lease 120 cycles per second and approximately 75 phase oscillations per cycle.

We now consider the desired phase density of the stacked beam for mode A operation. It is desired that the model be capable of stacking a two-day beam with a current density of 50 amperes in a radial aperture of one centimeter.* Such a beam occupies an energy spread of 1.96 Mev and hence a phase area of

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*As will be pointed out in Section V, rf scattering will decrease this current density for the earliest increments of beam. However, for the later increments of beam, the current density approaches its "unscattered" value. Hence for the phase area considerations of mode A operation, we base our calculations on a current density of 50 amperes per centimeter of radius.

$\Delta A = \frac{\Delta E \, \Delta \phi}{\omega}$ = 0.54 volt-seconds. If we can expect to stack one ampere of beam, or 3×10^{11} electrons, in both directions with each bucket, it should be possible to produce the desired beam by repeating the process 50 times. The phase area of the bucket as it passes into the stacking region must be limited to 1/50 of 0.54 volt-seconds or 0.011 volt-seconds. At the given fm rate, the 250 volt bucket will have a phase area of 0.0165 volt-seconds. To reduce this area, the cavity voltage and/or the fm rate must be reduced. It is advantageous to leave the fm rate unchanged and reduce the cavity voltage adiabatically to a value closer to its critical value of 170 volts ("Brinksmanship"). This reduces the phase area of the bucket rapidly but reduces the frequency of phase oscillations only slightly. By reducing the cavity voltage to 225 volts before passing the bucket through the stacked beam, its area decreases to the required 0.011 volt-seconds, the stable phase angle moves to 49°, and the frequency of phase oscillation is 5.9 kilocycles.

Next we calculate the conditions under which the beam must be captured at the beginning of the rf cycle. Since the bucket area is tailored to 0.011 volt-seconds in the stacking process, and allowing a factor of two for phase area growth during acceleration, we must capture the beam in a phase area of 0.0055 volt-seconds. Assuming that the energy spread of the injected beam is sufficiently small, this can be done by suddenly turning on a stationary bucket of this area. A stationary bucket at 2 Mev having an area of 0.0055 volt-seconds requires a cavity voltage of 15 volts.

The frequency of phase oscillation for electrons in this bucket is 7 kilocycles, and it increases as $V^{\frac{1}{2}}$. Using the criterion that the voltage may be doubled in

$1\frac{1}{2}$ periods of phase oscillation, we need of the order of one millisecond to increase V adiabatically from 15 volts to 250 volts. While the voltage is increasing, the frequency modulation may be started gradually in such a way that the stable phase angle moves from $\phi_s = 0$ when the voltage is first turned on to the eventual $\phi_s = 43^o$ of the main acceleration period.

For mode B operation, the phase density is diluted by a factor of two by stacking alternately filled and empty buckets in both of the stacked beams. For this mode of operation, we will be content to stack a two-way beam of 50 amperes in a radial aperture of two centimeters. Arguments similar to those above require that the pickup voltage be 15 volts, and that approximately one millisecond is required to increase this voltage adiabatically to 500 volts. The phase area of the 500 volt bucket (0.023 volt-seconds) can be reduced to the required phase area of 0.011 volt-seconds by adiabatically reducing the rf voltage to 421 volts as the stacking region is approached. The stable phase angle moves to $5.^o$.

A limit is placed on the permissible energy spread of the 2 Mev electron beam by the requirement that this beam must have an area in phase space of .0055 volt-seconds, or less. This corresponds to an energy spread of $\pm$ 12,000 electron volts or a percentage spread of $\pm$ .65 %.

The mean energy of the beam of 2 Mev electrons and the initial rf frequency must be closely matched if the electrons are to be captured. The matching may be done empirically by maximizing the accelerated beam. It is essential, however, that the betatron energy and the rf frequency be stable enough to maintain such a match once it is found. It seems reasonable to require the betatron energy to be stable to about 1/5 of the energy spread or $\pm$ 3 kev.

The percentage frequency variation corresponding to a $\pm$ 3 kev energy variation is

$$\frac{d\omega}{\omega} = K \frac{dE}{E} = \pm .000087 \text{ or } \pm .0087\%.$$

The rf system must have this stability at the beginning of the rf cycle.

The displacement oscillator serves to replace energy lost by the stacked beam to synchrotron radiation. This energy loss for the 40 Mev two-way beam amounts to 2.91 electron volts/turn.* This amounts to an energy loss of .277 Mev in 1/240 second, or a phase displacement of .076 volt-seconds. This radiation loss can be overcome by a displacement oscillator having a bucket area of .076 volt-seconds passing down through the stack 240 times a second. A 404 volt bucket which is modulated from 22.91 to 23.08 megacycles/second in 1.7 milliseconds has the required phase area of .076 volt-seconds.

The sequence of events for the displacement oscillator are as follows:

1. A 404 volt bucket is turned on rapidly at 22.91 megacycles.
2. The bucket is frequency modulated in a linear fashion from 22.91 to 23.08 megacycles/second in 1.7 milliseconds. The bucket must neither increase nor decrease appreciably in phase area as it passes through the stacked beam.
3. The gap voltage is turned off rapidly and the frequency of the master oscillator is recycled to 22.91 megacycles/second.

The entire process will require 2 milliseconds. For mode A operation, the process will be repeated four times in succession during the first eight milliseconds

*This value depends strongly on the details of the orbit scalloping, and is based on an estimate of this effect by George Parzen. MURA-376

of the main acceleration period. For mode B operation, the process will be repeated two times during the first four milliseconds of the main acceleration period. In either case the process is repeated 240 times/second.

For a pair of 50 ampere beams (a total of 3×10^{13} electrons), the total rate of energy loss by synchrotron radiation amounts to 321 watts. The total power stored in the beam is 192 Joules.

V. SCATTERING OF THE STACKED BEAM BY THE RF BUCKETS

When an rf bucket passes through a stacked beam, the beam not only suffers an average phase displacement equal to the area of moving bucket, but it is also scattered in energy. The rms scattering depends on both the size and the γ of the rf bucket.* It has been estimated that for a γ of .7 that the rms scattering is $.7 \times \overline{\Delta E}$, where $\overline{\Delta E} = \frac{A_s \omega}{2\pi}$ and where A_s is the phase area of a stationary bucket having the same rf gap voltage as the moving bucket. For a γ of .2, the rms scattering is estimated to be $.25 \times \overline{\Delta E}$.

On this basis we can estimate the total energy spread for the 50 ampere beams described in the phase area consideration of Section IV. Mode A operation requires that 50 accelerating buckets and 200 displacement buckets pass through the beam stacking region during the buildup of the 50 ampere beam. The early increments of beam suffer scattering from all of the rf buckets, while the last few increments of beam suffer very little scattering. The latter increments of beam which lie just below 40 Mev, produce a current density close to the desired 50 amperes per centimeter of radius. The early increments of beam are scattered

* $\gamma \equiv \sin \phi_s$

around an energy of 38 Mev with an rms amplitude of

$$\langle \Delta E_A \rangle_{early} = \pm \sqrt{50\,(.219\ \text{Mev})^2 + 200\,(.104\ \text{Mev})^2} = \pm\ 2.1\ \text{Mev.}$$

The resulting current density is approximately as shown in Fig. 3.

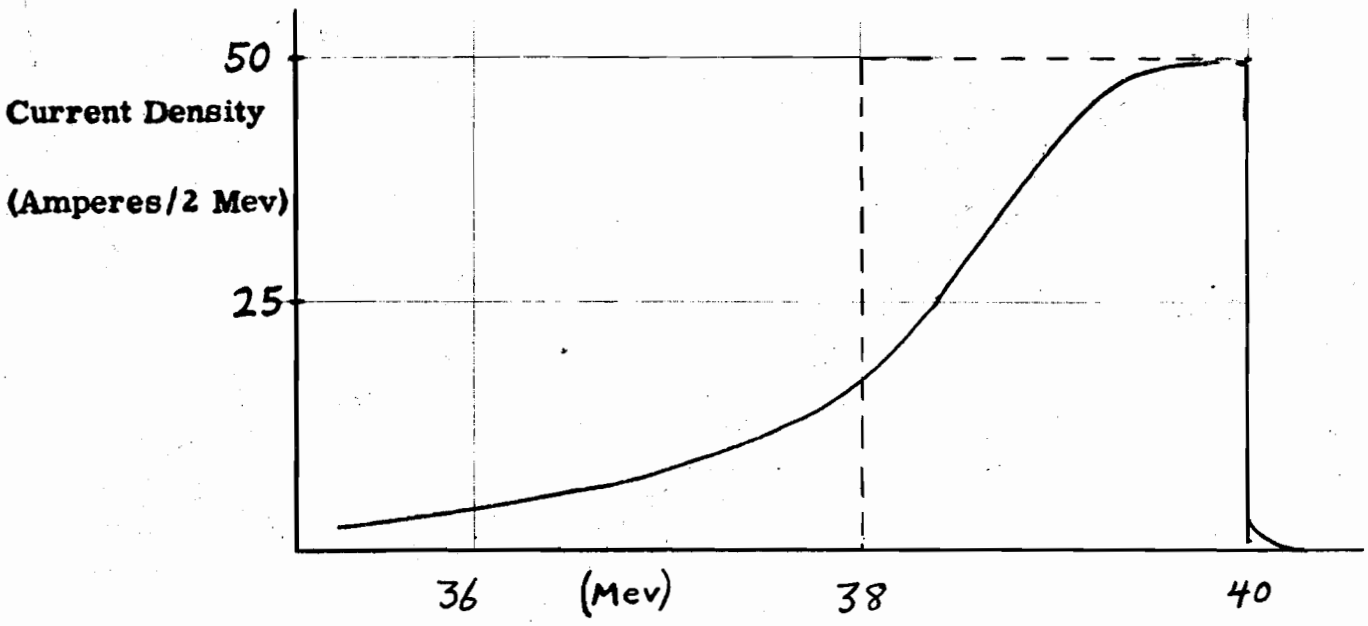

Fig. 3

The spatial current density is somewhat lower than the maximum current density shown in Figs. 3 and 4. Horizontal betatron oscillations spread the beam current out over an amplitude of $\pm \frac{1}{2}$ centimeter.

Mode B operation requires that 100 accelerating buckets and 200 displacement buckets pass through the beam stacking region during the buildup of the 50 ampere beam. For this mode, the early buckets are scattered about 36 Mev with an rms amplitude of

$$\langle \Delta E_B \rangle_{early} = \pm \sqrt{100\,(.300)^2 + 200\,(.104)^2} = \pm\ 3.3\ \text{Mev}$$

The resulting current density is approximately as shown in Fig. 4.

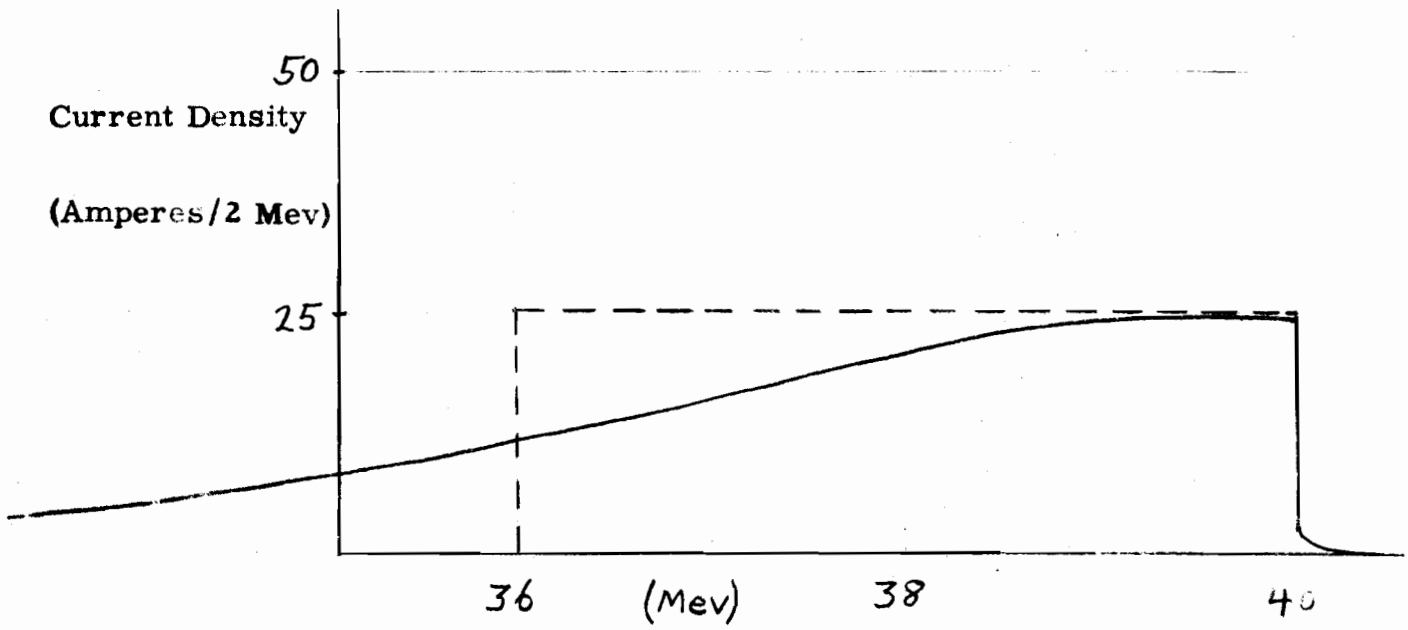

Fig. 4

Since the scattering goes as the square root of the time and the amount of beam goes directly as the time, the fractional effect of the scattering could be reduced by continuing the stacking process for longer than 50/60 second.

VI. GRAPH OF PARAMETERS

Fig. 5 presents a plot of the energy, revolution frequency, gap voltage, bucket area , effective radius of electron orbit, phase oscillation frequency and γ as a function of time for mode A operation. All parameters are plotted as unitless quantities as defined on the graph. The revolution frequency ω is given as a ratio to the transition frequency ω_T of 29.91 megacycles/second.

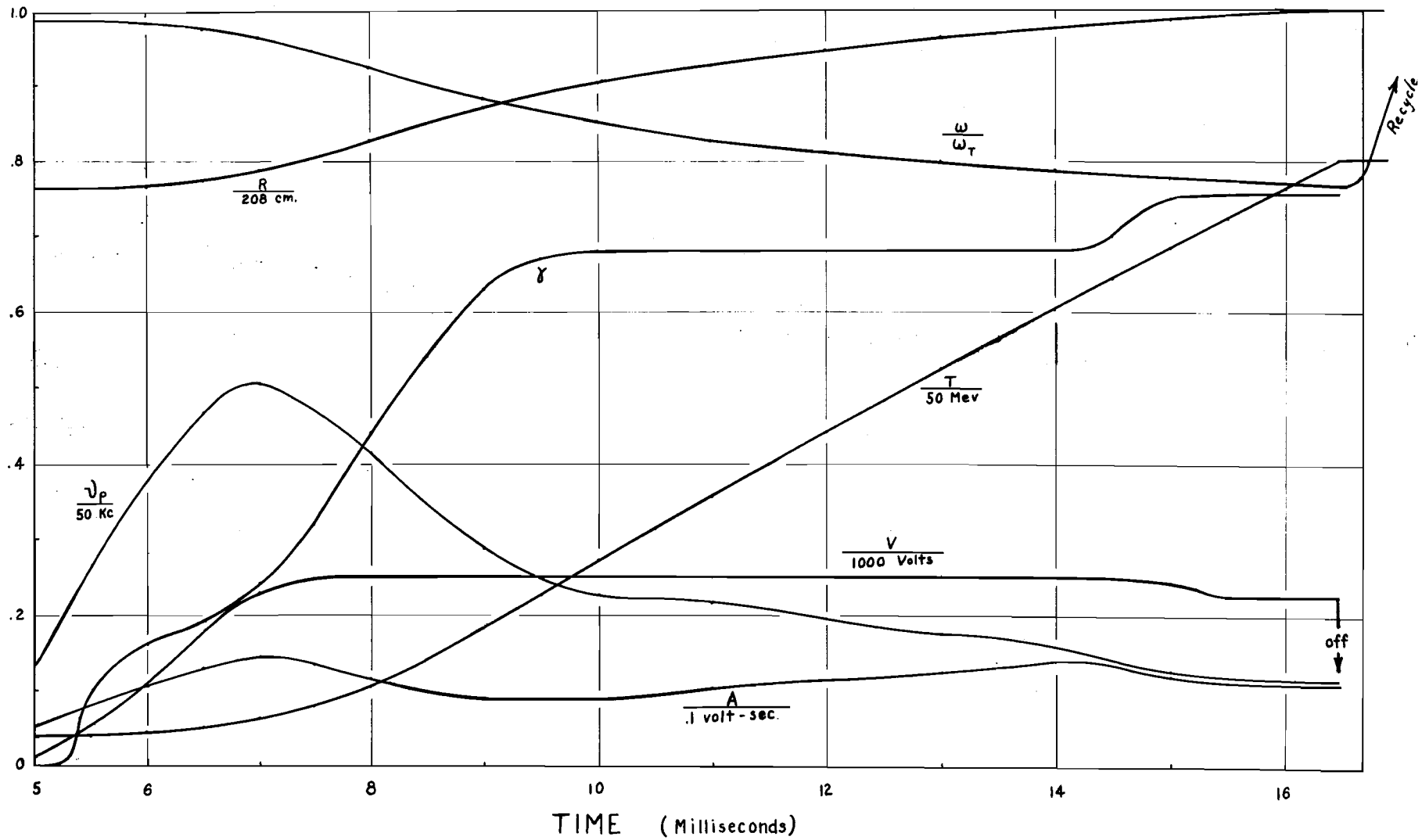
1.0
.8
.6
.4
.2
0
5
6
8
10
12
14
16
TIME (Milliseconds)
R / 208 cm.
ω / ω_T
γ
T / 50 Mev
ν_p / 50 Kc
V / 1000 Volts
A / .1 volt-sec.
off
Recycle

Fig. 1