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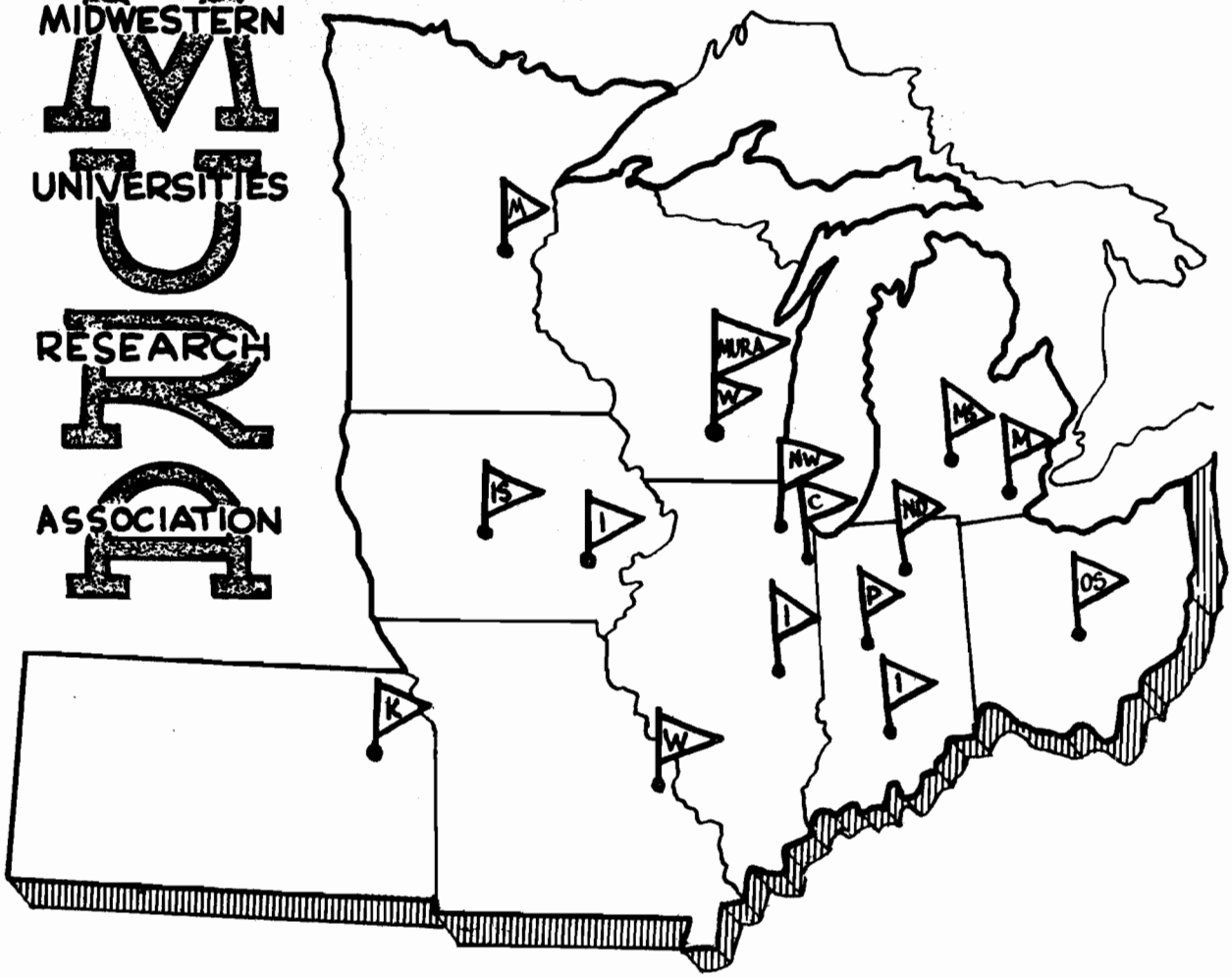

OPERATING CHARACTERISTICS OF THE RF SYSTEM FOR THE WISCONSIN MODEL

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OPERATING CHARACTERISTICS OF THE RF SYSTEM FOR THE WISCONSIN MODEL

Robert Stump**

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There have been a number of changes in the parameters of the r.f. system of the Wisconsin Model since the previous report on the r.f. (MURA 426). These changes, and some of the reasons for them, are described here.

Introduction

The main features of the acceleration and phase displacement r.f. systems are as described in MURA-426. The accelerating system can pick up particles with an energy of 2 Mev (29.48 mc) according to any amplitude program desired, carry the particles to 36 Mev (23.11 mc) and stack them there. The maximum available r.f. voltage on the gap over this frequency range is 500 volts. The system can operate from injection (20 mc) through transition (31 mc) at somewhat lower voltage.

The displacement system is required to restore energy lost by radiation to the stacked beam. This is done by passing an r.f. bucket through the stacked beam in the direction of decreasing energy, and phase displacing the stacked beam upward in energy. The system can supply on the gap a maximum of about 400 volts with a frequency range of about .5 mc. The time for the r.f. pass is about 1.75 milliseconds and this may be repeated at intervals of about 2 milliseconds.

Frequency Program

The frequency program of the acceleration cavity is quite arbitrary, the only restriction being that the rate of change of frequency, $\frac{df}{dt}$, be a slowly varying quantity. The voltage on the cavity must also be a slowly varying quantity, but $\frac{dV}{dt}$ may change rapidly. Thus, at turn-on the voltage should rise

slowly at first, but when reaching the desired level there may be a discontinuity in $\frac{dV}{dt}$ without causing any scatter in the particles.

For convenience in getting a beam, and not because these are the only programs possible, two r.f. frequency and amplitude programs have been calculated. These are given in Tables 1 and 2. Near the end of the acceleration cycle the amplitude should be reduced to shrink the bucket size so that the bucket will have the maximum phase density. This is an empirical adjustment, determined by the phase area of the particles in the bucket. Note that in both programs listed, the phase area grows uniformly during acceleration, so that no particles should be lost at intermediate energy even though some phase scatter may occur during acceleration.

Pickup

For a beam of low intensity the best pickup procedure is one which goes as slowly as possible. For example, if the voltage is "snapped" on to .34 volts, then increases at a rate

$$\frac{dV}{dt} = c\, V^{3/2}$$

with $c = 3.22 \times 10^3$, the voltage will increase iso-adiabatically (MURA-491) to 100 volts in one millisecond, and the phase scatter due to the turn-on will be less than 1.0×10^{-3} volt sec. With high currents, however, beam cavity interactions are severe, and a rapid rise in voltage is necessary. With 250 ma circulating beam, a linear turn-on from 0 to 100 volts in one millisecond would give about as little phase scatter as possible.

TABLE 1
Typical Frequency Program
500 Volts Maximum on Cavity

Time-Milli-seconds	Volts	Frequency Megacycles	Sin ϕ_s	Bucket Area Volt-Sec.	Kinetic Energy Mev
0	0	29.48	0	0	2.0
	(Voltage is raised to minimize beam-cavity interaction)				
2.000	500		0	.0318	2.0
	(Frequency program started slowly, details not important)				
2.50	500	27.73	.68	.0073	5.0
2.60	500	27.32	.70	.0073	6.0
2.80	500	26.65	.72	.0074	8.0
3.01	500	26.12	.75	.0075	10.0
3.21	500	25.69	.76	.0078	12.0
3.41	500	25.33	.78	.0080	14.0
3.62	500	25.02	.78	.0083	16.0
3.82	500	24.74	.79	.0085	18.0
4.03	500	24.50	.80	.0087	20.0
4.23	500	24.28	.80	.0090	22.0
4.44	500	24.08	.80	.0092	24.0
4.65	500	23.90	.81	.0095	26.0
4.85	Note	23.73	.81	.0097	28.0
5.06	500	23.58	.81	.0100	30.0
5.27	500	23.43	.81	.0102	32.0
5.48	500	23.30	.81	.0104	34.0
5.70	500	23.17	.81	.0106	36.0

Note: Voltage reduced at end to decrease bucket size. Empirical adjustment.

TABLE 2
Typical Frequency Program
250 Volts Maximum on Cavity

Time-Milli-seconds	Volts	Frequency Megacycles	Sin ϕ_s	Bucket Area Volt-Sec.	Kinetic Energy
					2.0
0.00	0	29.48	0	0	
.10	7.5		0	.0039	
.20	15		0	.0055	
.40	25		0	.0064	
.60	50		0	.0068	
.80	100			.0070	
1.00	200				
1.18	250	28.81	.54	.0070	3.0
1.44		28.22	.59	.0066	4.0
1.93		27.32	.63	.0069	6.0
2.40		26.65	.65	.0074	8.0
2.85		26.12	.67	.0076	10.0
3.30		25.69	.69	.0078	12.0
3.74		25.33	.69	.0086	14.0
4.19		25.02	.70	.0088	16.0
4.63		24.74	.71	.0090	18.0
5.08		24.50	.72	.0092	20.0
5.52		24.28	.73	.0092	22.0
5.97		24.08	.74	.0093	24.0
6.42		23.90	.74	.0097	26.0
6.87		23.73	.75	.0096	28.0
7.32		23.58	.75	.0100	30.0
7.77		23.43	.76	.0099	32.0
8.22		23.30	.76	.0102	34.0
8.68		23.17	.76	.0100	36.0

Displacement System

The energy loss due to radiation of a beam stacked at 36 Mev is much less than that given in MURA-426. The loss is 19.4 Mev/sec. This is made up by the phase displacement system with a cavity voltage of 186 volts, and a frequency modulation from 23.11 to 23.36 mc in a time of 1.75 milliseconds.

The r.m.s. scatter due to the phase displacement was investigated on the computer using the TTT program (MURA-225). By means of this program, the displacement of each of 80 particles, distributed uniformly in phase and at four energies, was found. In addition, more particles were examined in the region of phase where the particles were trapped near the bucket and carried down in energy instead of being phase displaced up. The results are given in Table 3.

The scatter due to the acceleration system is the expected scatter to particles much below the stacking energy. The reason for the discrepancy between the calculated energy displacement and the computer results was not investigated. It may have been due to the more rapid rate of frequency modulation leading to non-adiabatic effects. Certainly the scatter in this case is much worse.

The RMS scatter in case I may be compared with the results of Reilly (MURA-477). The scatter observed here is much greater than that found by Reilly. This is probably due to the fact that he carried the bucket only a short distance beyond the stack. Some of the particles are carried a long distance down in energy by the bucket and they contribute heavily to the RMS scatter. In the case of Reilly's work, these could not have been carried so far, since the

TABLE 3

I. Displacement System

Cavity volts - 200

Rate of f m $\frac{df}{dt} = 1.32 \times 10^8$

Stable phase $\sin\phi s = .46$

Calculated average displacement $\Delta E = .103$ Mev.

Computer results (from TTT):

$\overline{\Delta E} = .111$ Mev
RMS scatter $= .154$ Mev.*

II. Acceleration System

Cavity volts - 200

Rate of f m $\frac{df}{dt} = 2.3 \times 10^8$

Stable phase $\sin\phi s = .80$

Calculated average displacement $\Delta E = .0277$ Mev.

Computer results (from TTT):

$\overline{\Delta E} = .090$ Mev
RMS scatter $= .170$ Mev.*

* The symbol after RMS scatter should be:

$$\left[\frac{\Sigma(\Delta E - \overline{\Delta E})^2}{n}\right]^{1/2}$$

bucket was turned off just after it passed the stack. In the Wisconsin Model the large fm range is necessary to accommodate the energy spread expected in the stack.

The phase displacement system will be heavily loaded by the beam. Any shift in amplitude or phase during the passage of the r.f. bucket would trap particles in the bucket and decelerate them. Thus, much more power is required in the r.f. amplifier than the voltage and band-width would indicate. The system should work satisfactorily with beams of up to one-hundred amperes with an energy spread of about 2 Mev. At higher densities, minor modifications may be required.

Limitations on Beam Density

The density of the stacked beam is limited by a number of factors. If a bunch of electrons with no energy spread and with the same amplitude of betatron oscillation were injected and accelerated by adiabatic processes, the energy spread in the stack would be zero and any number of buckets could be stacked at the same energy. However, many processes spread the energy of the bunch so the number of buckets which may be stacked in a given energy range is limited. The phase area of a beam stacked in a radial width of one centimeter at 36 Mev is

$$A = \frac{2\pi \Delta E}{f} = .50 \text{ volt sec.}$$

If fifty buckets are to be stacked, the area of each must not exceed .01 volt sec.

Neglecting non-adiabatic effects during acceleration, the after causes of spreading are listed below.

1. Variation in injector voltage.

This is quite negligible. The energy spread is much under one kilovolt. If this were the only effect, the phase area of a bucket to hold the particles would be less than 3×10^{-4} volt sec.

2. Variation in betatron acceleration.

The long term drift of the accelerating voltage is less than $\pm .4\%$. The short term drift is less than this by a factor of 4. The corresponding phase areas are:

Long term drift $A = 2 \times 10^{-3}$ volt sec.

Short term drift $A = 5 \times 10^{-4}$ volt sec.

3. Variation in frequency due to betatron oscillations.

The frequency of a particle with large amplitude betatron oscillation is lower than one of the same energy with no oscillation. The frequency difference is given by:

$$\frac{\Delta f}{f_o} = \frac{a_x^2 \nu_x^2}{4} + \frac{a_y^2 \nu_y^2}{4}$$

(Note: This does not agree with the formula given in the TTT writeup, MURA-225. Westlund is correcting the TTT program.)

From MURA-373

$$a_x = .011$$

$$a_y = .012$$

$$\nu_x = 6.36$$

$$\nu_y = 5.34.$$

This gives, at injection, a frequency spread

$$\frac{\Delta f}{f} = 2.26 \times 10^{-3}$$

There will also, therefore, be a spread in the betatron acceleration acquired by the particles of the same amount

$$\frac{\Delta E}{E} = 2 \times 10^{-3}$$

Due to adiabatic damping, the frequency spread expected at r.f. pickup is

$$\frac{\Delta f}{f} = 3.08 \times 10^{-4}$$

With this frequency spread, the minimum phase area of the particles obtained when the r.f. turn-on frequency is in the middle of the frequency range, is 3×10^{-3} volt sec.

If for some reason the betatron oscillations are excited to the stability limit at pickup, the phase area is 2×10^{-2} volt sec.

4. Error in turn-on frequency.

The r.f. system gives the correct turn-on frequency better than one part in 10^4. This would lead to a phase area of less than 2×10^{-5} volt sec.

5. Non adiabaticity at turn on.

For a small beam, an iso-adiabatic turn-on as described above would lead to a phase spread of less than 1×10^{-3} volt sec. However, with a beam of 250 ma, beam cavity interactions would give a phase scatter of about 1×10^{-2} volt sec. with the present tuning of the cavities. For more intense beams, it may be necessary to retune the cavities to minimize beam cavity effects, or to load the cavities more heavily and be content with lower accelerating voltages.

These processes limit the density of a stacked beam at any energy. In addition the scatter due to the phase displacement system will further dilute the beam. This dilution is reduced at lower energies since the radiation losses are smaller, and fewer displacement cycles are required. At 36 Mev, the present phase displacement system would give a RMS scatter of .121 Mev per pass, or a scatter of 1.87 Mev/sec.