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# THE RF PROGRAM FOR LAMPF II

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The rf program is chosen to maintain a bucket/bunch area ratio of at least two during rf capture, acceleration, injection, and extraction. At 0.797 GeV the beam bunch area is 0.0635 eVs. We show the behavior of the rms bunch length and dp/p during acceleration. The rf system must provide a voltage of 1.59 MV/turn for the booster and 5.0 MV/turn for the main ring.

## I. Introduction

In this work we describe the operation of the rf system for both the LAMPF II booster and main ring. These facilities are being proposed for a high-intensity kaon factory. The 1 mA LAMPF Linac would be an $H^-$ injector for the booster. After stripping to $H^+$, the booster would accelerate $1.5 \times 10^{13}$ protons from 0.797–7.3 GeV kinetic energy. The repetition rate would be 60 Hz. Four booster pulses fill the main ring in box-car fashion. The main ring then accelerates $6 \times 10^{13}$ protons from 7.3–45.0 GeV with a repetition rate in the 3–4 Hz range. In Sec. II we describe the magnet program and rf system requirements. In Sec. III we discuss the injection and acceleration in both machines as well as the matching. Beam loading and power requirements are treated in Sec. IV.

## II. System Requirements

### A. Booster

The $16^{2/3}$ ms cycle includes 1 ms for injection, 11.75 ms for acceleration, and 3.92 ms for reset. The power supply has been described by Praeg.[1] The time-dependent magnet waveform dictates an energy gain/turn given by

$$\Delta E_s(t) = \frac{C\pi f_a}{c}\,(p^+c - p^-c)\,\sin(2\pi f_a t) \qquad (1)$$

where C is the circumference C = 350.87 m, $f_a$ is the acceleration magnet rise frequency $f_a$ = 42.55 Hz, and $p^-/p^+$ is the initial/final momentum ($p^-$ = 1.463 GeV/c and $p^+$ = 8.185 GeV/c). The peak $\Delta E_s$ = 1052 KV/ turn. A single rf system delivers an energy gain/turn for the synchronous particle given by $\Delta E_s = eV_o \sin\phi_s(t)$ where $\phi_s$ is the synchronous phase angle, and $V_o$ is the net cavity voltage.

### B. Main Ring

Initially we considered a magnet waveform similar to that of the booster but with a 3 Hz cycle. A cycle includes 50 ms for injection of four booster pulses, 87.5 ms for acceleration, 166.67 ms for slow extraction and 29.167 ms for reset. We evaluate Eq. (1) with C = 1323.32 m, $p^-$ = 8.185 GeV/c, $p^+$ = 45.929 GeV/c, and $f_a$ = 5.714 Hz; the maximum $\Delta E_s$ = 2.99 MeV. We have also considered an accelerating magnet waveform which is linear $\dot{B}$ = constant. In this case the energy gain per turn is $\Delta E_s(t) = C(dp/dt)$. We may adopt this procedure in the future, but in this work we just consider the sinusoidal waveform of Eq. (1).

## III. Dynamics

### A. Booster RF Capture

The LAMPF micropulses will be injected for one macropulse (≤1.0 ms). The rf frequency is 50.3125 MHz and the harmonic number $h = f_{RF}/f_{rev}$ = 70. The micropulses will be prebunched to a 19.7 ns spacing and synchronously injected into sixty of the booster rf buckets. A hole of ten buckets must be left for the extraction process. The rf capture voltage is 700 kV/turn. The injected particles occupy ±100° of rf phase with bunch area 0.0635 eVs and $\Delta p/p$ = ±0.3%. The ratio of bucket to bunch area is ~2. Figure 1 shows the stationary bucket and beam bunch for the booster with $1.50 \times 10^{13}$ protons in the machine. The reduction in bucket area due to longitudinal space charge is small (~2.0%). The small-amplitude synchrotron tune $\nu_{so}$ is 0.044.

### B. Booster Acceleration

The voltage $V_o$ and phase $\phi_s$ were chosen to supply the required $\Delta E_s(t)$ as specified by Eq. (1). Figure 2(a) shows the time dependence of $V_o$, $\phi_s$, $\nu_{so}$, and the bucket area $A_b$.[2] The program was chosen to conserve the bucket area until $V_o$ reached 1.59 MV, then to hold this voltage until 6.0 ms into the cycle, after which $V_o$ is reduced linearly to its final value of 1 MV; $\phi_s$ is $\sin^{-1}(\Delta E_s/eV_o)$.

We have calculated the time dependence of the rms bunch length θ (in units of rf phase) and the rms dp/p which we call δ. Figure 3 shows these two quantities obtained using the rf program shown in Fig. 2(a). An envelope equation is used for the time dependence of θ using the prescription of Sacherer.[3] The equation is written as[4]

$$\frac{d}{dt}\left(\frac{1}{r}\frac{d\theta}{dt}\right) + s\theta + \frac{\Omega f_L}{\theta} - \left(\frac{S}{\pi}\right)^2\frac{r}{\theta^3} = 0 \qquad (2)$$

where $r = -h^2\eta/(mR^2\gamma)$, $s = -eV_o\cos\phi_s/(2\pi h)$, S is the r.m.s. longitudinal area of the bunch, R is the machine radius $(C/2\pi)$, $\eta = 1/\gamma^2 - 1/\gamma_t^2$, and m is the proton mass. The term $\Omega f_L$ represents the longitudinal space-charge force. Ω is equal to $3r_p mc^2 h/R$ where $r_p$ is the classical proton radius $r_p = 1.54 \times 10^{-18}$ m and $f_L$ is given by

$$f_L = \left[\frac{g_o}{2\gamma^2} - \frac{\beta}{Z_o}\left|\frac{Z_L}{n}\right|\right] N \qquad (3)$$

where $\gamma = E/m_pc^2$, $Z_o$ is the impedance of free space $Z_o$ = 377 ohms, and $g_o = 1 + 2\ell n(b/a)$, where b/a is the ratio of beam pipe to beam diameter (~ 2 at injection). The broadband wall impedance term $Z_L/n$ acts in an opposite sense, and N is the number of protons in a bunch. The expression for δ is

$$\delta = \frac{hcS}{Rpc\pi}\left[\left(\frac{\pi}{Sr}\frac{d\theta}{dt}\right)^2 + \left(\frac{1}{\theta}\right)^2\right]^{1/2} \qquad (4)$$

For the booster we assume $|Z_L/n|$ = 10 ohms, N = $2.5 \times 10^{11}$ protons, $\gamma_t$ is imaginary $\gamma_t$ = 11i, and S = 0.0635/4 eVs. Equation (2) was numerically integrated using a fourth-order Runga-Kutta method. The final values are θ = 0.252 (14.4°) and δ = 0.092%.

### C. Main Ring Injection

Four successive batches of $1.5 \times 10^{13}$ protons from the 60 Hz booster are injected into the main ring at intervals of $16^{2/3}$ ms. The filling process takes 50 ms and stacking is done in box-car fashion. Each batch is separated by e.g., six empty buckets to allow for rise and fall times of the injection kickers. The main ring harmonic number is 264 so the $6 \times 10^{13}$ protons are

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stored in 240 bunches. The rf voltage for the 50 ms injection phase is 1 MV/turn and the bucket area is 0.788 eVs. This value is much larger than the injected beam area (the bunch area is 0.0635 eVs).

D. Main Ring Acceleration

The voltage $V_o$ and phase $\phi_s$ were chosen to supply the required $\Delta E_s(t)$ as specified by Eq. (1). Figure 4(a) shows the time dependence of $V_o$, $\phi_s$, and the bucket area $A_b$.[2] The program was chosen to conserve the bucket area until $V_o$ reached 5.0 MV, and then to hold this value throughout the acceleration; $\phi_s$ is $\sin^{-1}(\Delta E_s/eV_o)$. Figure 5 shows the time dependence of the rms $\theta$ and $\delta$. We used $\gamma_t = 6.0322$, $|Z_L/n| = 10$ ohms, and the booster value for S (0.0635/4 eVs).[5] The final values are $\theta = 0.244$ and $\delta = 0.017\%$.

E. Matching

The output booster values $\theta = 0.252$ and $\delta = 0.092\%$ are unequal to the required starting values for the main ring $\theta = 0.383$ and $\delta = 0.061\%$ (see Fig. 5). Matching can be effected by performing rf manipulations in the booster just prior to extraction. One technique to increase the booster bunch length is just to reduce the rf voltage abruptly, from say, 1.0 MV to 0.25 MV. After 50-100 turns the bunch will have lengthened to the correct value expected in the main ring and the beam can be transferred. A second technique is to shift the rf phase by $\pi$ to the unstable fixed point for a preset number of turns, and then shift back by $-\pi$ and wait for a similar number of turns. With an rf voltage of 1 MV the whole process will take about 30 turns for the bunch to lengthen to the desired value.

## IV. Beam Loading and Power Requirements

With strong beam loading the rf cavities must be detuned off resonance an angle $\psi$ in order to maintain the required energy gain/turn.[6] The angle is given by $\tan\psi = (I_b/I_o)|\cos\phi_s|$ where $I_b$ is approximately 1.8 times the first harmonic of the beam current (at the rf frequency). The current $I_o = V_o/R_{sh}$ where $R_{sh}$ is the total shunt resistance of the cavities. The ratio of the power delivered to the beam divided by the power dissipated in the cavities is denoted by $R_p$ and is given by $R_p = (I_b/I_o)\sin\phi_s$. We define the power dissipated in the cavities as $P_c = V_o^2/(2R_{sh})$.

For the booster we require $R_p < 1.0$; with a flux of $1.5 \times 10^{13}$ protons and the rf program shown in Fig. 2(a), this leads to a total shunt resistance of 535.2 KΩ. For this case we show in Fig. 2(b) the time dependence of $R_p$, $\psi$, and $P_T$ where $P_T$ is the total power delivered to the beam and cavities. The maximum generator power is near 4.5 MW. With sixteen cavities the maximum cavity voltage would be 100 KV, and the maximum power dissipation would be about 150 KW per cavity. The amplifiers would have to be capable of 280 KW output over a 20% frequency swing (due to the change in β during the acceleration).

For the main ring we require $R_p < 2.0$; with a flux of $6.0 \times 10^{13}$ protons and the rf program shown in Fig. 4(a), this leads to a total shunt resistance of 3864 KΩ. For this case we show in Fig. 4(b) the time dependence of $R_p$, $\psi$, and $P_T$ where $P_T$ is the total power delivered to the beam and cavities. The maximum generator power is near 9.75 MW. With forty cavities the maximum cavity voltage would be 125 KV and the maximum power dissipation would be about 81 KW per cavity. The amplifiers would have to be capable of 245 KW output over a 0.6% frequency swing.

## V. Conclusions

The rf dynamics seem to be in reasonable shape. Some changes may be in order for the main ring rf system regarding the large detuning angles. Feedback systems need to be considered to cope with the Robinson stability criteria.[7]

## References and Footnotes


1. W. Praeg, IEEE Trans. Nuc. Sci. NS-30, 2873 (1983).
2. C. Bovet, R. Gouiran, I. Gumowski, and K. H. Reich, "A Selection of Formulae and Data Useful for the Design of A.G. Synchrotrons," CERN/MPS-SI/Int. DL/70/4.
3. F. J. Sacherer, CERN/SI/Int.DL/70-12(1970)
4. W. W. Lee and L. C. Teng, IEEE Trans. Nuc. Sci. NS-18, 1057(1971).
5. We may need to raise the emittance in order to lower the peak currents. The effects of bunched-beam instabilities would thereby be reduced.
6. See e.g., J. E. Griffin, in "Physics of High-Energy Particle Accelerators," AIP Conf. Proc. No. 87, 564(1981).
7. K. Robinson, CEAL-1010 (1964).


## Figure Captions

Fig. 1. Injection stationary bucket for booster for $V_o = 0.7$ MV. Dots represent beam bunch generated uniformly in $\phi$-dp/p space.

Fig. 2(a). RF program for booster during the 11.75 ms acceleration cycle. $V_o$ is rf voltage, $\nu_{so}$ is the small-amplitude synchrotron tune, $\phi_s$ is the synchronous phase angle, and $A_b$ is the bucket area.

Fig. 2(b). Booster beam loading parameters plotted vs time. $R_p$ is the ratio of power delivered to the beam to that dissipated in the rf cavities, $\psi$ is the detuning angle, and $P_T$ is the power delivered by the generator.

Fig. 3. Behavior of rms quantities $\theta$ and $\delta$ calculated using Eqs. (2) and (4) during booster acceleration.

Fig. 4(a). RF program for main ring during the 87.5 ms acceleration cycle.

Fig. 4(b). Main ring beam loading parameters plotted vs. time. The quantities are defined as in Fig. 2(b).

Fig. 5. Behavior of rms quantities $\theta$ and $\delta$ during main ring acceleration.

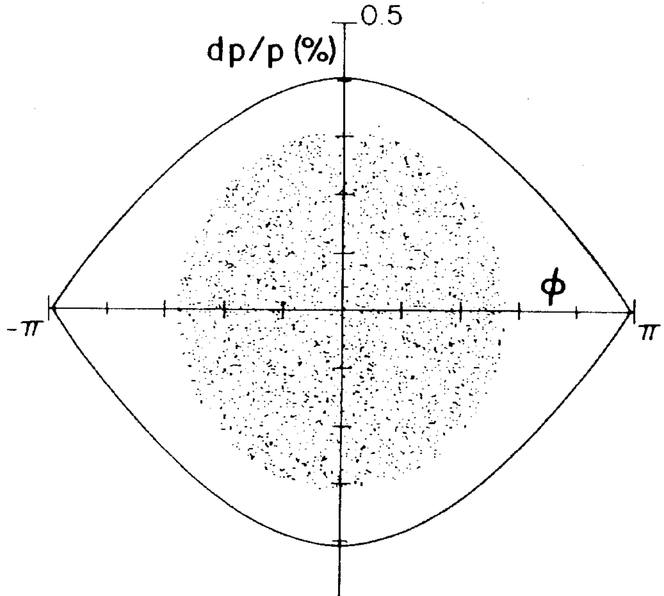


Fig. 1

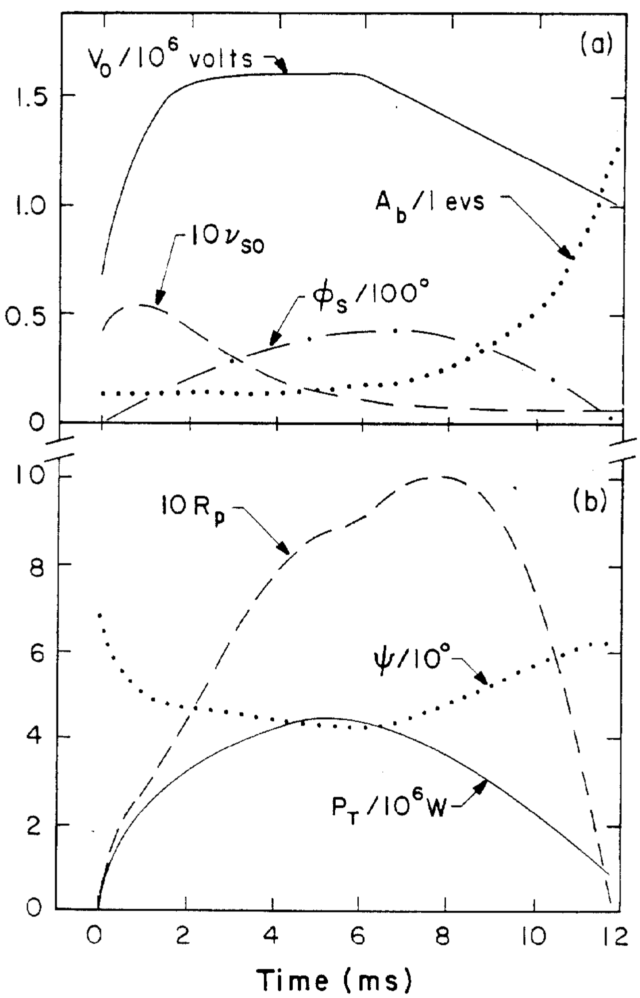


Fig. 2(a) and 2(b)

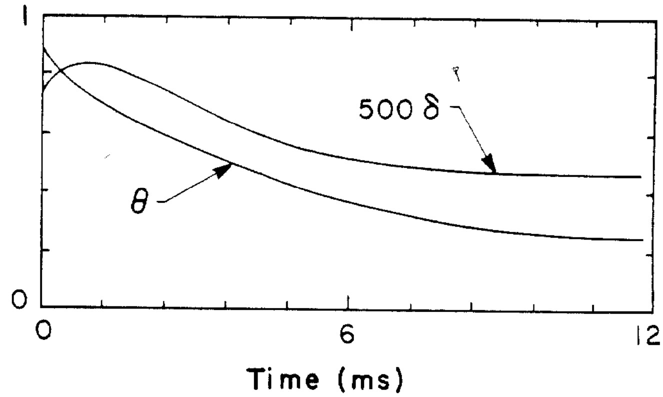


Fig. 3

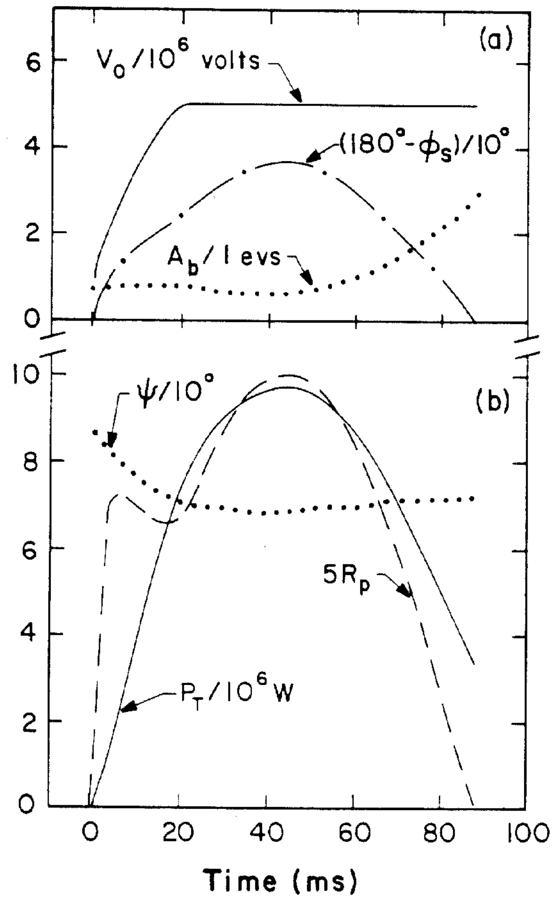


Fig. 4(a) and 4(b)

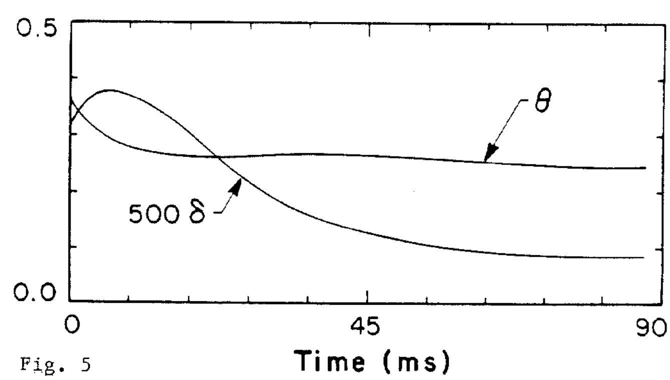


Fig. 5