$\bar{p}$ Note 410
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Proposal for Using 8 GeV Protons Delivered to the Debuncher Ring via the Main Ring for Studying and Evaluating Debuncher RF Performance

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I will describe here a scheme for using small ensembles of proton bunches delivered via the Main Ring for evaluating some aspects of Debuncher rf performance. The scheme has two major features. First, it is shown how to develop proton bunches with an aspect ratio such that Debuncher RF "debunching" can be studied along with the momentum aperture of the ring. Second, a technique will be described for establishing the correct phase of the Debuncher rf system even though the rf frequency is not consistent with the bunch spacing of 8 GeV protons delivered from the Booster.

1. How to Get a Useful Aspect Ratio

I assume that the Booster will deliver an ensemble of ten adjacent bunches, each containing about 10^9 protons, at T=8.02 GeV. for this example I assume that the longitudinal emittance of each bunch will be 0.07 eV-sec. and that the bunches would match Main Ring buckets of area ~ 1 ev-sec. (i.e., MR rf voltage 10^6 volts) <u>if</u> the Main Ring rf were on. In fact, for this scenario the Main Ring rf voltage will remain off. This corresponds to bunches matched to buckets generated by a Booster rf voltage of 325 kV at extraction. Except for intensity and number of bunches these are close to "normal" operating rf conditions. The Booster rf bucket height is ~25 MeV and a bunch matched to the bucket will have an energy half-height of 9.6 MeV. The full bunch length (~95%) will be about 4.6 nsec. A phase-space sketch of the bunch is shown in Figure 1a.

After injection into the Main Ring the bunches are allowed to drift with no rf. Below transition the higher momentum portions of the bunch will move to earlier times and vice versa. The drift rate is

$$\frac{\Delta t}{t} = -\eta \frac{\Delta p}{p}$$

where, at 8 GeV in MR η=0.0082 and

$$\frac{\Delta p}{p} = \beta^{-2} \frac{\Delta E}{E}$$

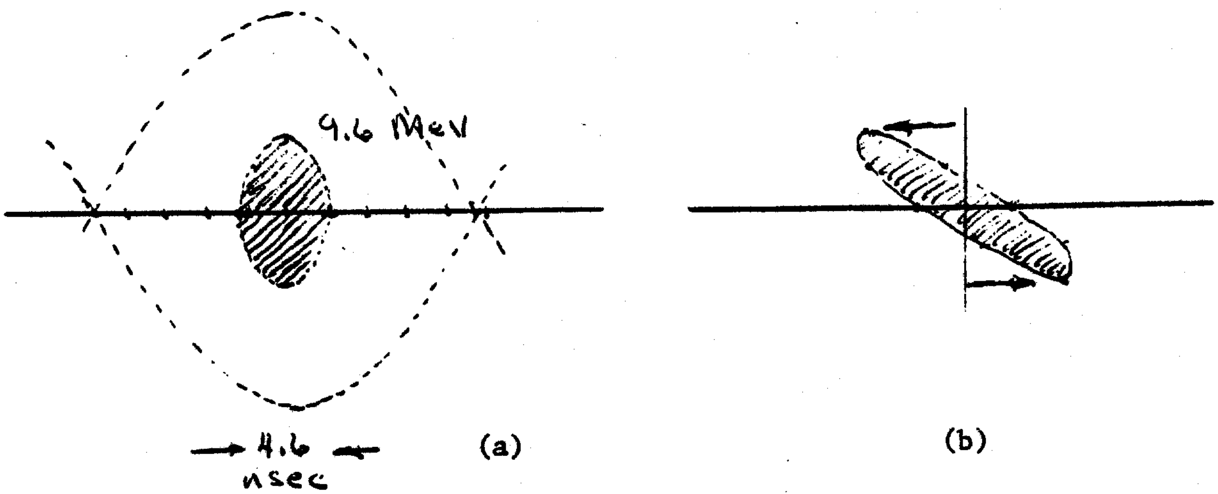

FIGURE 1

(a) Phase space plot (~95%) of 0.07 eV-sec bunch injected into Main Ring at T=8.02 GeV from 325 kV Booster bucket. Dotted outline is Booster bucket separatrix prior to extraction.

(b) Same bunch area after the bunch is allowed to drift in the Main Ring for 561 microseconds.

The peak deviation of the bunch was

$$\frac{\Delta p}{p} = (0.99445)^{-2} \frac{9.6\times10^{6}}{8.9\times10^{9}} = 1.09\times10^{-3}$$

$$\frac{\Delta t}{t} = -(8.2\times10^{-3})(1.09\times10^{-3}) = 8.9\times10^{-6}$$

If we choose to allow the peaks of the bunch to drift ±5 nsec with respect to the center, the drift time will be

$$t = \frac{5\times10^{-9}}{8.9\times10^{-6}} = 561\times10^{-6} \text{ sec.}$$

During this time the ±5 MeV points on the bunch will drift $\pm2.6\times10^{-9}$ sec from their starting displacements and the bunch will look roughly like that sketched in Fig. 1b. The distorted bunches have the same longitudinal emittance and momentum spread as the injected bunches but the charge projection, or current pulses, extend over about 11 nsec. The time spread and aspect ratio of the bunches injected into the Debuncher is obviously variable by varying the drift time. Also, these parameters will be affected by the longitudinal emittance of the bunches delivered from the Booster. The example used here is representative but not necessarily correct.

2. Bunch Evolution in the Debuncher Ring

I assume here that bunches like those in Figure 1b are injected into the Debuncher with the Debuncher rf voltage at 4.5 MV and frequency about 53.105 MHz, i.e., h=90. (More about the exact frequency and phase later). Debuncher η=0.0061.

The rf bucket height in the Debuncher will be 215 MeV, equivalent to a momentum spread ±2.44 percent. A bunch injected at the center of such a bucket will appear as sketched in Figure 2a. After one quarter of a phase oscillation period, about 37.5 turns or 63 microseconds, the distribution will appear roughly as shown in Figure 2b. At this time the bunch energy spread will be ±171 MeV corresponding to a momentum spread of ±1.9 percent. The full time width of the bunch at this time should be less than one nanosecond so this distribution is a reasonable simulation of an incoming bunch of antiprotons. After another quarter period the distribution will appear roughly as sketched in Figure 2c. At this time the rf voltage can be reduced as planned and attempts at adiabatic debunching can be started.

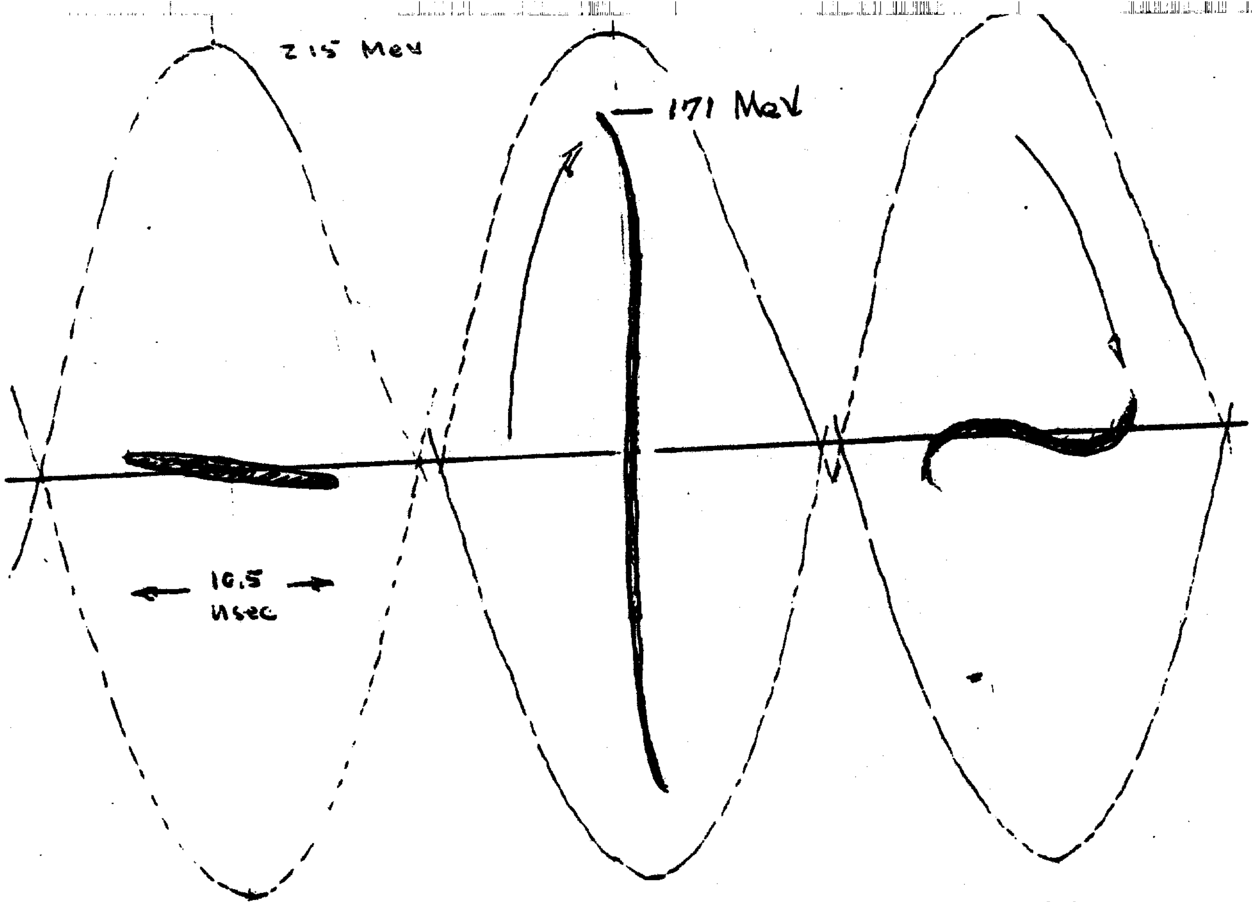

FIGURE 2

(a) "Sheared" 8 GeV bunch with momentum spread $\pm 1.1 \times 10^{-3}$ as it appears in a Debuncher bucket immediately after injection.

(b) Same bunch after one quarter phase oscillation period.

(2) Same bunch after one-half phase oscillation period.

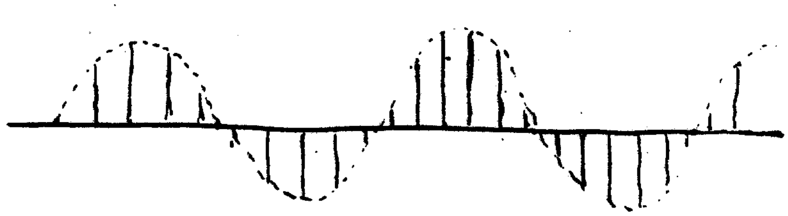

Figure 3. Phase detector output for initial frequency separation

In this manner many features of the Debuncher performance can be tested in a controllable way.

If each bunch contains 10^9 protons then useable signals can be developed in a broadband pickup with coupling resistance of 10 ohms. The bunch evolution described could be recorded in a mountain range display spanning perhaps one phase oscillation period. The subsequently adiabatically debunched ensemble may eventually be studied by Schottky scan.

It may also be possible to debunch the ensemble of ten bunches into an h=4 bucket at this point. Use of the h=4 diagnostic rf system will be treated in another note.

3. Frequency Mismatch and Phase Matching

Bunches extracted from the Booster at 8.02 GeV have a spacing of 18.9347 nsec corresponding to a frequency of 52.8130 MHz. The Main Ring rf frequency at the nominal $\bar{p}$ production energy of 120 GeV is 53.103477 MHz corresponding to a bunch spacing of 18.8312 nsec. If a particular bunch, preferably near the center of the ensemble, is centered in a Debuncher bucket, the adjacent nearest neighbors will be displaced from the bucket centers by ±0.104 nsec. The fifth bunches on either side of the centered bunch wil be displaced by ±0.52 nsec. With the bunch spread out to ±5 nsec these displacements will have a negligible effect on the bunch rotations described in Sec. 2.

A more difficult question is how to arrange the Debuncher rf phase so that the center bunch of the ensemble will be phased correctly with respect to the Debuncher rf phase at extraction/injection. Information about the relative phase of the ten-bunch ensemble in the Main Ring can be derived from the output of the MRRF low-level system leveling module. The signals will be constant amplitude bursts of ~53 MHz rf reflecting the phase and frequency of the ensemble each time it passes a fixed point in the Main Ring. The quality of this information will not be affected by the drift debunching described above unless the drift is allowed to continue until the phase spaces overlap longitudinally. These bursts of rf can be compared in a phase detector to the Debuncher fixed rf frequency. The result will be a series of pulses appearing at the Main Ring rotation frequency. The amplitude and sign of the pulses will reflect the relative phase of the bunch ensemble to the fixed frequency rf at each passage. The amplitude of each pulse will vary over its duration reflecting the ~5 degree relative phase shift of the two signals during the pulse and the average value of the pulse can be interpreted to reflect the phase relationship of the center bunch (or two bunches) to the fixed frequency rf at each passage. If the phase detector has a $\sin\Delta$ or $\cos\Delta$ response to inputs with relative phase Δ then the envelope of the train of output pulses will be a sinusoidal wave with period approximately eight Main Ring rotation periods as sketched in Figure 3.

The logarithmic derivative of the relative phases of two frequencies is equal to the logarithmic derivative of the frequency difference.

$$\frac{\Delta\theta}{\theta} = \frac{\Delta\omega}{\omega_1} = \frac{\Delta f}{f_1} \qquad \Delta f = f_2 - f_1$$

At f_1 (the Booster extraction frequency) the total phase shift in one turn around the Main Ring is $\phi=(2\pi)(1113)$ radians.

The log derivative of frequency is

$$\frac{53.103477-52.8130}{52.8130} = 5.5001\text{x}10^{-3}$$

where 53.103477 MHz represents 120 GeV in MR. The phase shift between the two inputs in one Main Ring turn then becomes

$$\Delta\theta = (1113)(2\pi)(5.5001\text{x}10^{-3})=(6.12162)(2\pi) \text{ radians}$$

If the Debuncher rf frequency is adjusted very slightly, to 53.103638 MHz then the phase shift per turn becomes $\Delta\theta=(6.125)(2\pi)$ radians per turn and the pulse pattern of Fig. 3 will repeat exactly every eight turns. (The required frequency shift is 161 Hz corresponding to a displacement of the buckets by 0.05% in momentum space. The new frequency corresponds to an extraction energy in the Main Ring of 126.6 GeV. The Debuncher rf system can easily be tuned to such a frequency).

The pulse train resulting from this frequency shift is still arbitrary in its composition because there is no apriori relationship between the Booster phase and the Debuncher phase at the moment of extraction. The signal train might look like one of the several examples in Figure 4. By changing the phase of the reference signal one can move through the various patterns of error signals. Ideally one would like the error signal to look like the last pattern in which every eighth pulse has zero net area. This situation can be established automatically by the following steps.

1. A non-retriggerable one-shot is set to fire on any positive excursion greater than some preset discriminator level. The time duration of the one-shot is set to about 7.5 Main Ring rotation periods. T_o, or about, 158 microseconds. In this way, as long as the error pulse remains above threshold the one-shot will trigger on the same phase error signal once each beat period.

2. A second one-shot, with period $1.5T_o$ is triggered on the leading edge of the first one-shot output.

3. A third one-shot, with period 42.25 microseconds, is also triggered on the leading edge of the first gate.

These gates can be combined, as shown in Figure 5, so that the second phase detector pulse following the trigger pulse is measured and held. The track-and-hold output signal is filtered and delivered to a phase shifter

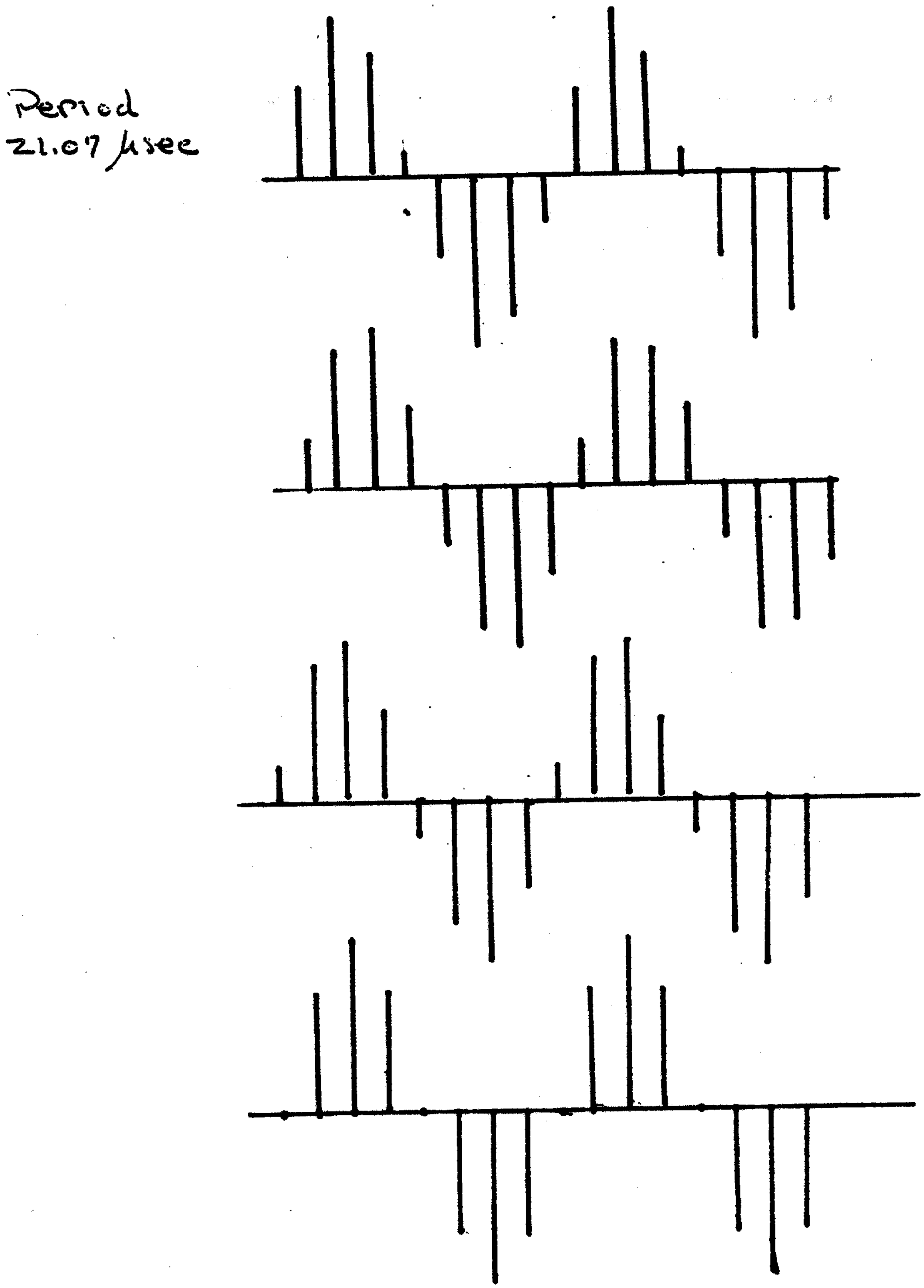

FIGURE 4

Several different phase detector outputs resulting from different initial phases.

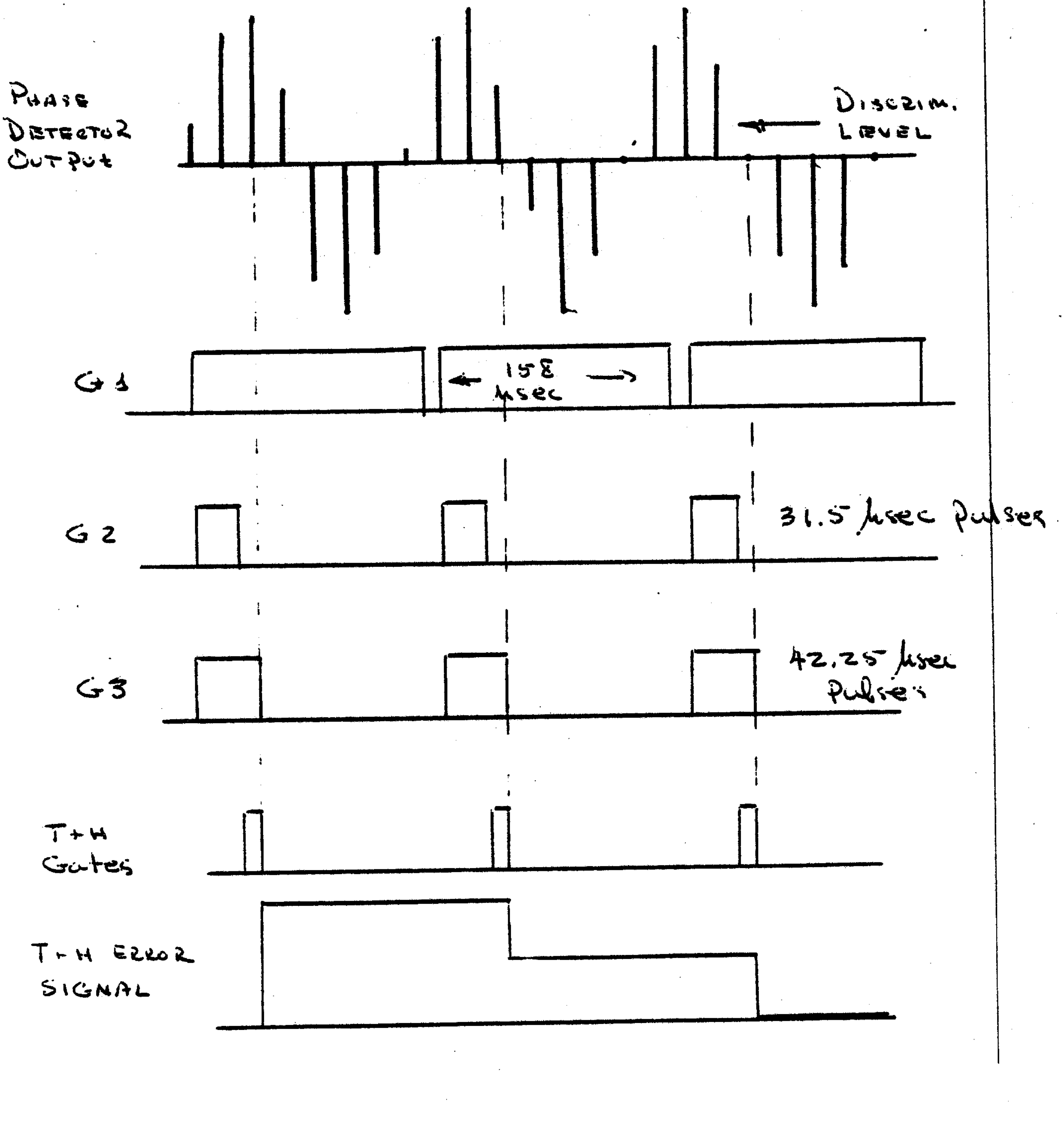

FIGURE 5

Gates and signals associated with phase adjustment of Debuncher rf. Here complete adjustment is implied after two beat periods.

in serires with the reference rf signal so that the rf phase is moved in a direction so as to minimize the sampled phase error pulse. This phase adjustment will always work in such a way as to increase the initially selected trigger pulse unless it is already a maximum, in which case the sampled pulse will be at zero.

The result of all this is that the phase of the reference rf, and of the Debuncher cavity rf, will have a known relationship with the average phase of the circulating bunch ensemble which repeats each eight Main Ring turns. If extraction of the bunch ensemble is triggered at a fixed time following the trigger pulse described here then the Debuncher rf phase can be adjusted so that the bunches are centered in Debuncher buckets in a repeatable way.

An outline of the required electronics is shown in Figure 6. The electronics, including the reference oscillator, should probably be assembled at the Main Ring low level system at FØ. The phase adjusted reference rf can then be delivered in the normal manner to the $\bar{p}$ source 10 building where it can be delivered to the Debuncher rf system in completely standard configuration. The rf bursts to be compared with the reference frequency are available as a monitor output on the leveling module with no modification. The required extraction timing pulses will then be available at FØ where they are required for coding the MRBS clock. The reference frequency and extraction delay will have to be adjustable through the control system.

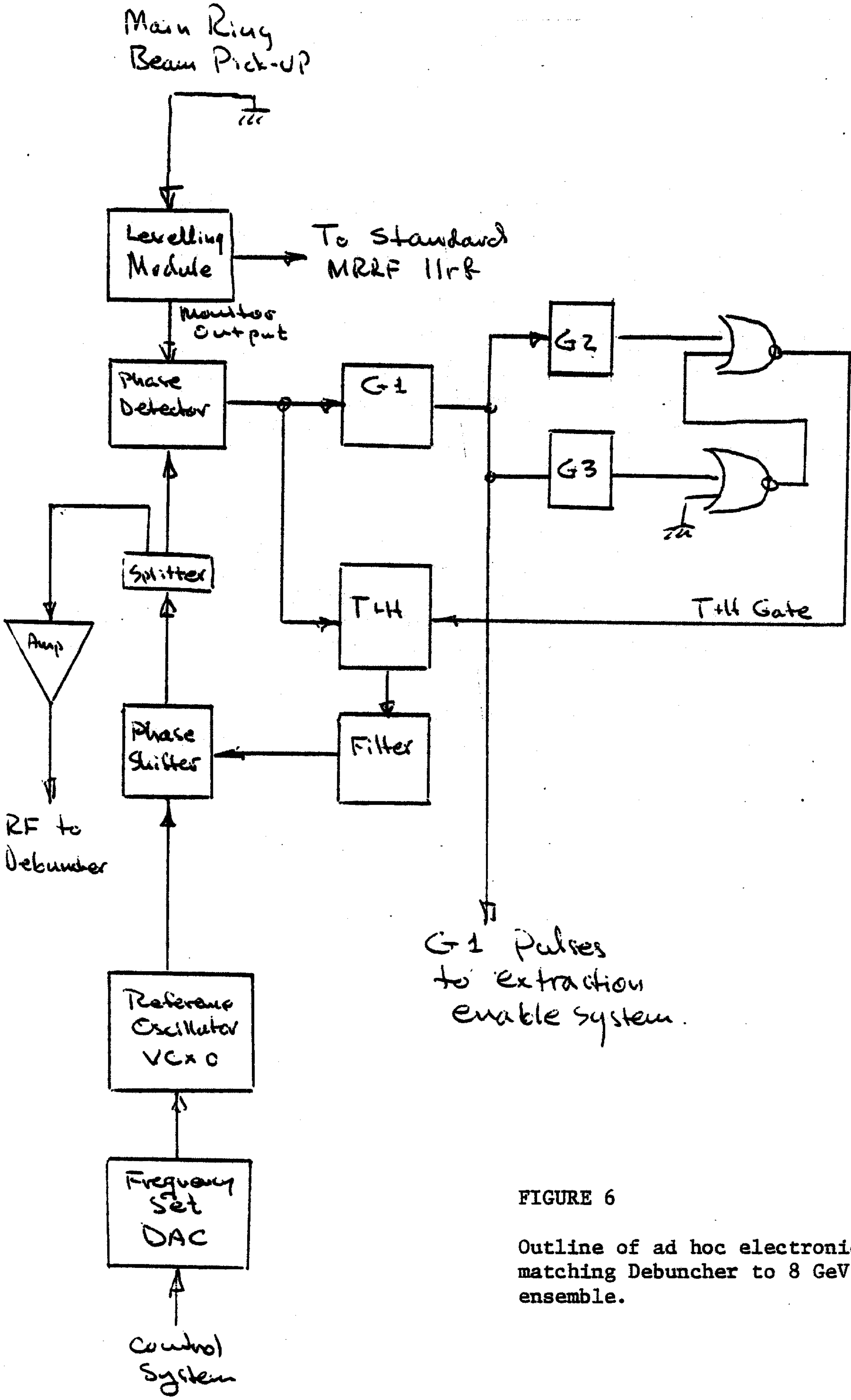

FIGURE 6

Outline of ad hoc electronics for phase matching Debuncher to 8 GeV proton ensemble.