FERMILAB-TM-2710-AD

MAIN RING LOW LEVEL RF

PART I

INTRODUCTION AND DESCRIPTION OF BLOCK DIAGRAM

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Introduction

The systems which comprise the radio frequency equipment for the main accelerator at Fermilab provide the accelerating potential for the proton beam. The acceleration takes place in resonant cavities through which the protons pass each revolution. An electromagnetic RF field is set up in these cavities, which for proper operation must be the correct amplitude, frequency and phase. The equipment which controls the amplitude and supplies the power for amplification is generally referred to as the high level RF equipment (HLRF). The system which generates the RF wave, and controls its frequency and phase is known as the low level RF system (LLRF).

The primary function of this manual will be to describe as thoroughly as possible the LLRF system. In doing so however it will be necessary to mention many of the components of the HLRF system.

Description of Block Diagram

This description is intended to be read while consulting the block diagram. Please keep in mind that a more detailed description of the individual modules, and the devices external to the block diagram, but which pertain to the low level system follows. Also included separately are pictures of the signals.

As mentioned in the introduction, the function of the low level system is to provide a RF wave with the correct frequency and phase to the high level system where it is amplified and used to excite the cavity. With this in mind, the simplest block diagram is the following:

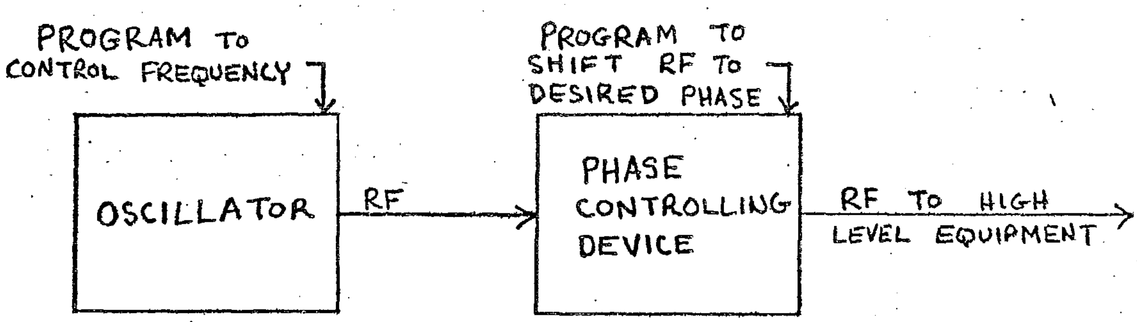

FIGURE 1

In reality the low level system is not a lot different from what is depicted in Figure 1. The oscillator and the phase shifter both exist as do the programs which control them. What is missing from the diagram are the feedback systems which ensure that the frequency and phase are correct, timing information, protection circuitry, communication with booster LLRF, etc.

The frequency controlling system and the phase controlling system will be discussed separately.

Frequency Control System

In order to accelerate any protons, the frequency of the main ring RF must be correct at all times throughout the cycle. What the frequency will need to be varies throughout the cycle. During injection it must be exactly equal to the final frequency of the booster RF. After acceleration begins, the RF must be the right frequency corresponding to the velocity of the protons. To ensure that both of these conditions are met, the feedback loop references two different sources at different times during the cycle. For further discussion, refer to the block diagram.

The devices which maintain the correct frequency are located in the upper left-hand corner. We will be considering the BEAM CURRENT MONITOR, AMPLITUDE LEVELING MODULE, DUAL PHASE DETECTOR, VCO, and INJECTION FREQUENCY REFERENCE OSCILLATOR.

The actual oscillator which produces the the RF wave is the module labled VCO (voltage controlled oscillator). It receives a program called FRQ from the curves MAC which maintains a nearly correct frequency throughout the cycle. The VCO also receives an error signal from a module called the DUAL PHASE DETECTOR (DPD). The DPD forms the error signal in the following manner. The VCO feeds back through a delay cable the RF it is generating. This signal enters the DPD as an input.

There are two additional input signals into the DPD. The first is a RF wave from the INJECTION FREQUENCY REFERENCE OSCILLATOR at a constant frequency of 52.813 MHz. The other signal is an RF signal produced by the beam. You will recall that the beam travels around the ring in groups of protons called bunches that are spaced one RF wave length apart. A plot of proton density passing a given point vs. time would then be a RF signal. It is the fundamental component of this signal which is fed into the DPD.

Inside the DPD the feedback signal from the VCO is split and the two resulting signals are mixed with the other above mentioned input signals in DBM 166 VARI-L mixers. The property of these mixers is that they will produce an error signal proportional to the phase difference between the two inputs.*

The final function of the DPD is to provide a means of determining which error signal will be sent to the VCO. A gate signal is applied called the INJECTION GATE. While this gate signal is high the error signal outputted from the DPD will be the signal generated by comparison with the reference oscillator. When the gate goes low, the error signal will be the one generated by comparison with the beam signal. The time at which the gate changes is controlled by a Main Control Room timing channel called ACCSW.

Due to the properties of the mixers which actually provide the error signal, the amplitude of the inputs must be constant for the error signal to be only phase dependent. Clearly the beam signal will vary greatly in amplitude as the intensity varies, and therefore the AMPLITUDE LEVELING MODULE (ALM) has been inserted between the BEAM CURRENT DETECTOR and the DPD. Its purpose is to provide a constant amplitude, phase stable signal for the DPD, regardless of main ring intensity.**

In summary of the frequency loop we seen that during injection time the frequency and phase at the output of the VCO is locked to that of the reference oscillator. After ACCSW time the feedback comes from the beam signal, and the VCO frequency is locked to the beam frequency.

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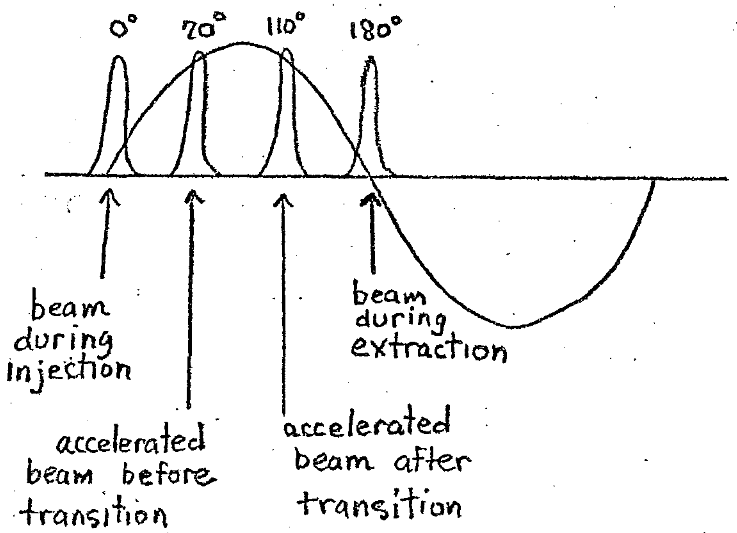
*If two signals of similar frequency in phase at all times, they will therefore be of the same frequency. This is noted because this is a frequency feedback loop, as well as providing a constant phase.

**It has recently been discovered that the present ALM does not provide a phase stable signal over a large dynamic range such as 100% slow spill. This places an additional burden on the phase shifter, and can cause a perturbation in the radial position.

Phase Control

So far the systems which maintain the correct frequency of the RF have been discussed. Also important in the acceleration of beam is the phase of the RF when the protons cross the accelerating gap in the cavities. The normal stable phase angle in main ring is 60°-70° (I'll refer to it as 70° in the remainder of this paper). However, in order to maintain a proper radial position a feedback loop monitors the radial position and slightly shifts the RF around this stable phase angle to give the beam more or less energy as needed. Therefore this will be referred to as the radial feedback loop.

During injection and extraction when no acceleration is taking place the stable phase angle is ∅° & 180°, respectively; and after transition the stable phase angle must be shifted to ~ 110°. Therefore, in addition to radial feedback, the phase control portion of the low level RF must account for these conditions.



Note: although the diagram implies that the beam shifts with respect to the RF, actually the RF shifts with respect to the beam.

FIGURE 2

The actual shifting of the phase occurs in a module which directly follows the VCO. It is referred to on the block diagram as the PHASE SHIFTER I ACCEL PHASE CONTROL and in this paper PSA. Like the VCO it is a voltage controlled device. The degrees of phase the RF passing through it is shifted is proportional to its voltage input. Unlike the VCO, the PSA does not receive its program directly from the curves MAC. The program as well as the radial error signal is handled in another module, the RADIAL POSITION PROCESSOR (RPP), and from there fed to the PSA.

Referring to the block diagram, the radial feedback loop involves the modules labled COAXIAL DIRECTIONAL COUPLER, FILTER, RADIAL POSITION MEASUREMENT UNIT, and the RPP.

The COAXIAL DIRECTIONAL COUPLER is a stripline detector in the tunnel at E44 which sends two signals upstairs, each an RF signal from the beam. These signals are similar to the beam RF signal mentioned in connection with the frequency feedback loop, however, the two signals are picked up on radially opposite sides of the beam pipe and therefore their relative amplitudes depend on the radial position of the beam. The signals are appropriately attenuated and fed into the RADIAL POSITION MEASUREMENT UNIT (this unit is labled the HORIZONTAL BEAM DAMPER SYSTEM POSITION MODULE should you go out to the RF building and look for it. In this paper it's the RPMU).

The function of the RPMU is to provide a position signal. In doing so it can be considered a sum over difference detector which provides position information independent of beam intensity. The RPMU has two output signals which differ only in their response time. The "slow" output is filtered so it does not contain information about individual booster batches. It is the signal we are interested in with regards to the radial feedback loop (and is available in the MCR as a MADC channel called RPOS). The other output of the RPMU is the "fast" output. It is not filtered and has another use described later in this paper.

The RPOS signal is fed into the RPP. We are now regarding it as the radial error signal and theoretically the function of the LLRF is to maintain a zero error signal. There are two program from the curves MAC which also enter the RPP. One of these is called RAG and is the gain program on the radial error signal (RPOS). The second is known as the PHASE SHIFTER PROGRAM (PSP). Basically, the function of PSP is to provide for the large phase shifts that are required when going from injection to acceleration and then to extraction. More will be said about this after two more functions of the RPP are discussed. The RPP module receives two gates from the GATE GENERATOR.

The first of these is the RADIAL POSITION ENABLE GATE (RPEN). This gate is the inverse of the INJ. GATE. It remains low until ACCSW time and then goes high throughout the remainder of the cycle. While this gate is low the output of the RPP is zero volts. The second gate is called TRANSITION PHASE GATE (TPG). This gate goes high at transition time and flips the output of the RPP to the opposite polarity. Note that this gate is generated by a pulse from the curves MAC at the energy specified on page 8 of the MR530.

In the following discussion assume that a zero voltage output from the RPP to PSA means a zero degree phase angle of the RF with respect to the beam bunches. Of course this doesn't happen magically, but for the present discussion this assumption is valid.

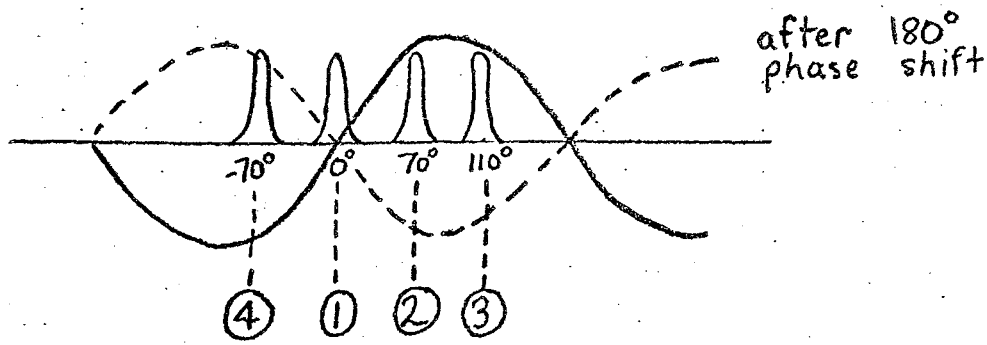


FIGURE 3

During injection the output of the RPP is clamped to zero in that the RPEN gate has not yet occurred (POS. 1 in Figure 3). As acceleration begins the PSP program provides a voltage which shifts the RF wave so that the beam is at POS. 2. A short time later, transition takes place in main ring. When this occurs, not only must the RF be shifted so that beam is on the opposite side of the wave (i.e., POS. 3) but the direction in which the feedback is acting must be reversed. In the RPP transition is noted by the occurrence of the TPJ gate. At this time the output polarity is reversed, which produces the desired effect in regards to the feedback, but rather than actually placing the beam at POS. 3 in Figure 3 it will have the beam located at POS. 4.

Clearly this is not the desired effect and this situation is remedied in a later module which also receives the TPJ gate and at that time inverts the RF signal producing a 180° phase change. This then produces the RF wave shown by the dotted curve in

Figure 3. The fact that the beam at POS. 4, with respect to the dotted curve, is identical in phase to the beam at POS. 3, with respect to the solid curve, can readily be seen.

During extraction the output of the RPP will ideally return to zero, which will return the beam to POS. 1, and since the later 180^o phase shift is still in effect beam will be at the 180^o phase angle desired for extraction.

The output of the RPP is called PSHIFT or phase shifter drive signal and is reviewed below.

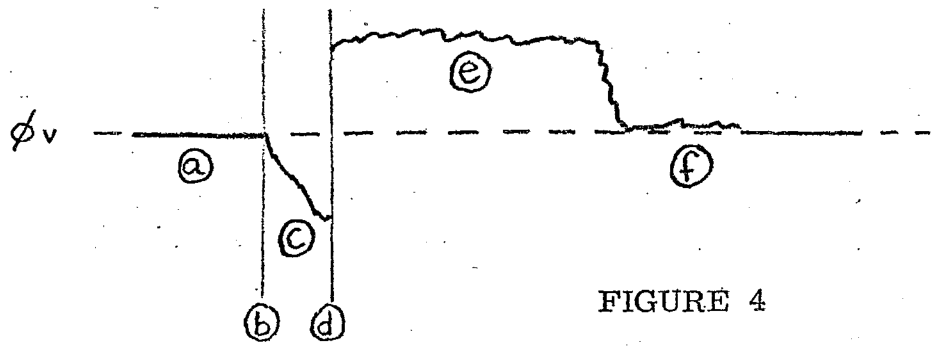


FIGURE 4

a Zero output during injection time. The RPP output is clamped to zero volts asking for no phase shift or feedback compensation.

b ACCSW occurs and the RPEN gate goes high allow the feedback loop to begin functioning, and also unclamping the output of the RPP. ACCSW could have been set earlier during injection but I have shown it at its recommended time, just before acceleration begins.

c Acceleration before transition: The PSA (phase shifter) is shifting the beam towards the 70^o phase angle.

d Transition: The TPJ gate has occurred the output of the RPP is flipped to the opposite polarity.

e Acceleration after transition: The PSA is shifting the beam -70^o with respect to the $\emptyset^o$ shift for zero volts.

f Extraction: The feedback loop is still enabled but with no acceleration. The phase shift needed by PSA is $\emptyset^o$.

The RF signal from the output of PSA is fed into the GATE AND FAN OUT DRIVER (GFD). In addition to a stage of amplification which produces a 6 volt p-p signal at its output, the GFD performs two functions corresponding to two gates it receives. One is the RF GATE which comes from the MAIN RING RF TIMING CONTROLLER and the UNIVERSAL LOGIC CHASSIS CARD shown in the lower portion of the block diagram. In the presence of this gate RF can pass through the GFD, without the gate it cannot. The second gate is the TRANSITION PHASE GATE (TPG) which was described earlier. It is this module that flips the RF wave the necessary 180^{o} at transition time and therefore the gate is needed. From the output of the GFD the RF enters the fan out system which distributes the RF signal to the RF-805 amplifiers at each RF system. From this point on the cabling for all stations is carefully phase matched.

Synchronization With Booster

In the description so far it can be seen that there is no feedback present until ACCSW time. Before ACCSW occurs the VCO is locked to the frequency of the reference oscillator and the radial feedback is not yet enabled. During this time the phase shifter drive signal is at zero volts providing ϕ^{o} of phase shift with respect to the incoming beam from booster. The components which provide the capability of injecting booster beam at the desired ϕ^{o} phase angle on the main ring RF wave are the subject of this section.

Referring to the block diagram note that the output signal from the VCO is split before going to PSA. The second signal from this splitter is fed into another phase shifter labled PHASE SHIFTER II INJECTION PHASE CONTROL on the block diagram and PSB in this paper. As far as the electronics are concerned PSB is identical to PSA.

The control voltage for shifting the phase of the RF in PSB is a DAC voltage called INJPHO, tunable in the MCR. The RF proceeds from PSB, through a RF-805 amplifier located at MRRF and on to booster. The booster LLRF uses this signal from main ring as a reference and phase locks the booster RF to it just prior to booster extraction. When INJPHO is changed the phase of the RF wave sent to booster will change. In effect this will change the phasing of the beam bunches coming from booster.

INJPHO can therefore be adjusted so that during injection time, when the main ring LLRF feedback is disabled, the beam bunches will arrive at the $\emptyset^{o}$ phase angle of the main ring RF wave.

Through the MR530, phase lock can be turned off. In doing so a coaxial relay just after PSB changes status and the booster receives an RF wave directly from the reference oscillator. Turn-PHLOCK off also produces a change in the MAIN RING RF TIMING CONTROLLER. This will be mentioned in the description of timing.

There is an additional parameter which can be adjusted in regards to the phasing of the main ring RF. It is called ACCPHO and is a DAC voltage controlled through the MR530 and applied directly to PSA. The ability to change ACCPHO is desired so that a smooth transition can take place when ACCSW occurs. In other words the correct way to tune ACCPHO is so that there is no overshoot or undershoot when the radial feedback is enabled. ACCPHO is not designed to have an appreciable effect during the acceleration of the beam in that the radial feedback should compensate for the change in ACCPHO. However, this is not necessarily the case as the following section on recent observations will point out. Also, since ACCPHO acts directly on PSA, it will change the phase of the main ring RF at all times, in other words it will change the phase during injection. If the incoming booster bunches were lined up on the 0^{o} phase angle before tuning ACCPHO it will then be necessary to retune INJPHO.

Loose Ends

The GATE GENERATOR (GG) in the lower left corner of the block diagram has been mentioned but not yet referred to directly. Its function is to process the timing pulses from the TIMING CONTROLLER and curves MAC and produce the gates (INJ, RPEN, TPG) that are used by the rest of the modules.

This basically describes the low level system. There are already several additional modules which are used to modify or improve beam quality and it seems premature to believe that there won't be more in the future. Each of these will be discussed separately so that it will be somewhat convenient to keep this paper up to date with the system.

Bunch Spreader

This feature was added to the LLRF in early 1975. It came in response to a request from experimenters for a more evenly populated longitudinal phase space, for more even spill.

A detector in the tunnel picks up the beam RF signal.

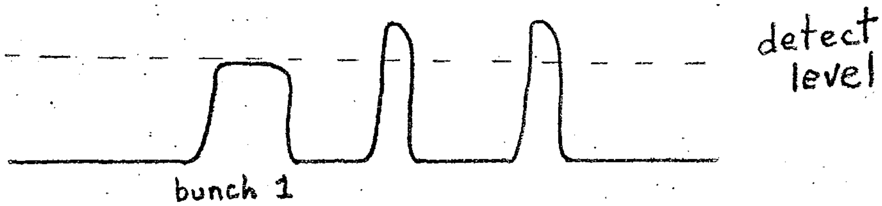


FIGURE 5

A diode detector picks off only the peaks of these beam bunches and passes this signal into the BUNCH SPREAD UNIT (BSU). The BSU receives this signal, filters it, amplifies it by the DAC voltage BSPR which is also applied to the module, and uses the resultant to amplitude modulate a 400 Hz signal. This 400 Hz signal is then applied to the RPP and therefore the PSA to shake the phase at a 400 Hz rate.

The BSU also gets a pulse at transition time. It uses the pulse to activate a delay circuit which enables the BSU a short time after transition and then turns it off. Therefore the BSU is active for only a short time after transition.

The 400 Hz signal is used in that it is roughly twice the synchrotron frequency. Again, note the amplitude of the 400 Hz signal going to the RPP is dependent on the peak amplitude of the individual bunches. If all the bunches were similar to bunch 1 in the figure, there would be no output.

Fast Feedback Loop

The FAST FEEDBACK LOOP came into existence in January 1976. It had been observed that at higher intensities just prior to transition there was a strong 48 KHz oscillation in the radial position. (48 KHz is the revolution frequency of the beam in main ring.)

This instability builds up just prior to transition and if not damped out the additional perturbation occurring at transition is sufficient to cause part of the beam to be lost shortly after transition.

In order to remove this unwanted oscillation the FAST OUTPUT from the RPMU is filtered for 48 KHz and used as an input to the PSA. There are two modules utilized in this feedback loop. They are labled on the block diagram as TRANSITION PHASE CONTROL (TPC) and the GATED INVERTER (GI). The TPC module contains the 48 KHz filter and provides gain control. The amount of gain is controlled by the DAC voltage called FFG which can be changed from the MCR. The TPC module also receives two pulses which control the time during which the feedback is active. The start gate comes from ACCSW and the stop gate from $T_{\emptyset}$ (main ring reset). Effectively, this does the same thing the RPEN gate does for the RPP and means that this feedback loop is not active during injection.

The feedback signal is then fed to the GI. As mentioned earlier while describing the radial feedback loop, the polarity of any feedback acting radially on the beam must change polarity at transition time. The GI receives the TPG and inverts the signal at transition time. The signal is then fed directly into the PSA through an auxiliary input.

The presence of this feedback loop has been instrumental in reducing beam loss at transition time.

Recent Observations

In the past few weeks, primarily through the interest of Helen Edwards to understand the effect of the low level system on extraction losses, some interesting things have been noted which became important in tuning. As mentioned earlier in this paper the radial feedback loop is designed to supposedly maintain a constant radial position throughout the cycle. At one time the system was designed with a radial offset program in mind so that the feedback loop would then maintain the radius at the radial offset program level. This is not now in use. (The Bunch Spreader uses the radial offset program input to the RPP.)

This procedure is feasible if an infinite gain on the radial feedback were allowed. It is of course not allowed, as certain instabilities arise. It has also been observed that extraction losses are sensitive to the feedback gain. Therefore the actual beam position becomes sensitive to all sorts of things. Recall that the PSP program is supposed to provide a gross, level changing voltage for the phase shifter, in order to accomplish the 0° to 70° and back to 0° shift. However, it is now found that in addition to doing this, the PSP also acts as a radial position program. Since the gain on the RPOS feedback cannot be high enough to totally minimize the error signal the other signal driving PSA therefore determines the orbit and this is PSP.

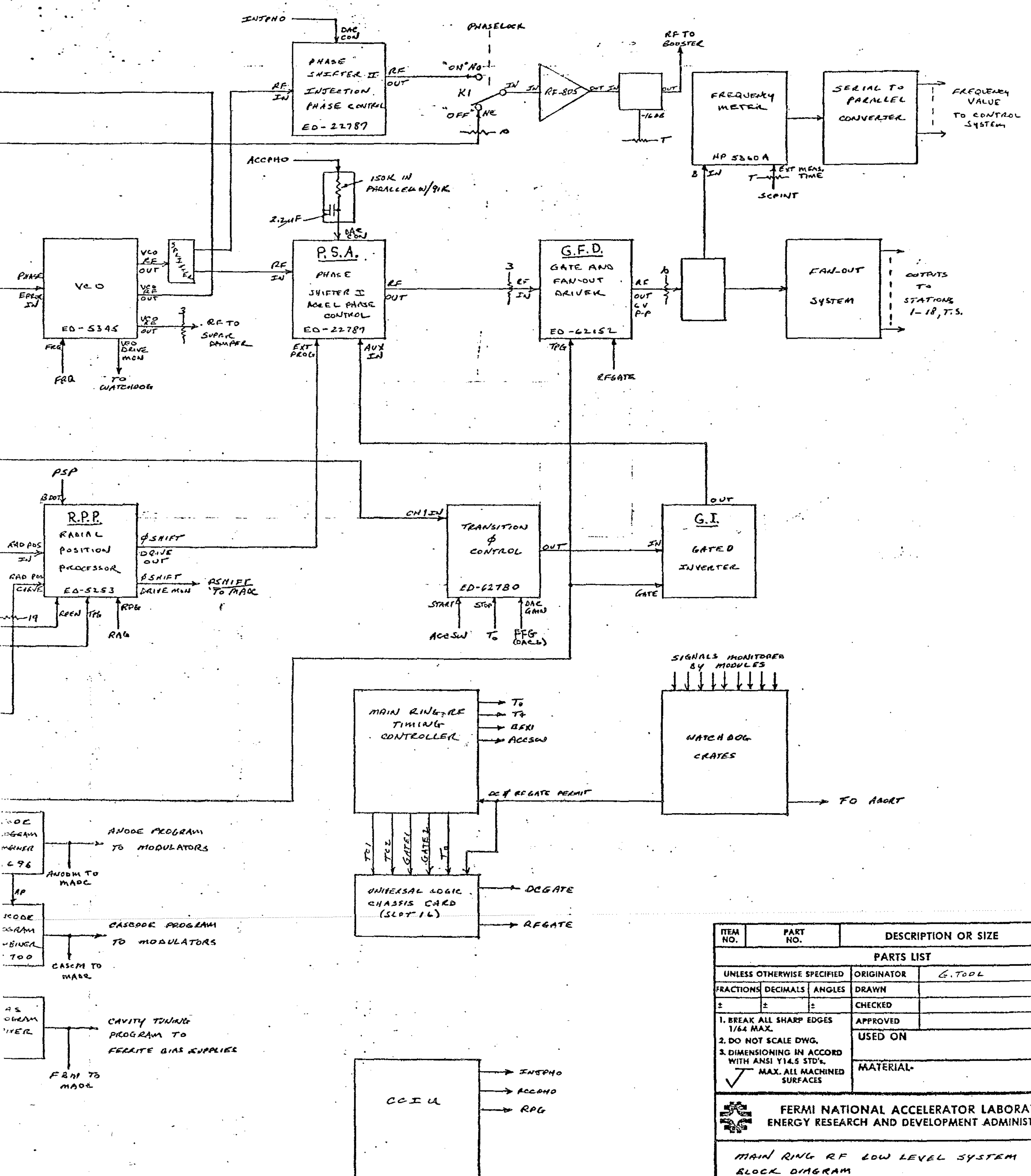
However, this isn't the only variable involved. Any change in the amplitude of the RF (a high level RF change) will call for the low level system to respond and drive the RF at a different phase angle in order to maintain the same orbit. But it has been demonstrated that the gain in the radial feedback is not sufficient to make up for these changes and therefore whenever an RF station trips off, or the anode program is changed the radius of the beam changes. Any time the radius of the orbit changes, extraction losses are effected.

Another parameter which has dramatic effects on the orbit of the beam throughout the entire cycle and even influences the radius during flattop is ACCPHO.

All of this again is due to the insufficient gain in the radial feedback loop. One possible solution is to create a learning feedback loop along the lines of QXR. In this case the PSP program would learn and therefore be synonymous to the memory in the QXR MAC. To reset the memory would return the PSP curve to that which is entered on page 8 of the MR530.

At any rate it seems likely that the main ring LLRF will continue to undergo changes and I hope to keep up to date on the changes and communicate them to the operations group.

REV.	DESCRIPTION	DRAWN
		APPD.



ITEM NO.	PART NO.	DESCRIPTION OR SIZE
		PARTS LIST

UNLESS OTHERWISE SPECIFIED				
FRACTIONS	DECIMALS	ANGLES	ORIGINATOR	G. TOOL
±	±	±	DRAWN	
			CHECKED	
			APPROVED	

1. BREAK ALL SHARP EDGES 1/64 MAX.
2. DO NOT SCALE DWG.
3. DIMENSIONING IN ACCORD WITH ANSI Y14.5 STD's.
✓ MAX. ALL MACHINED SURFACES

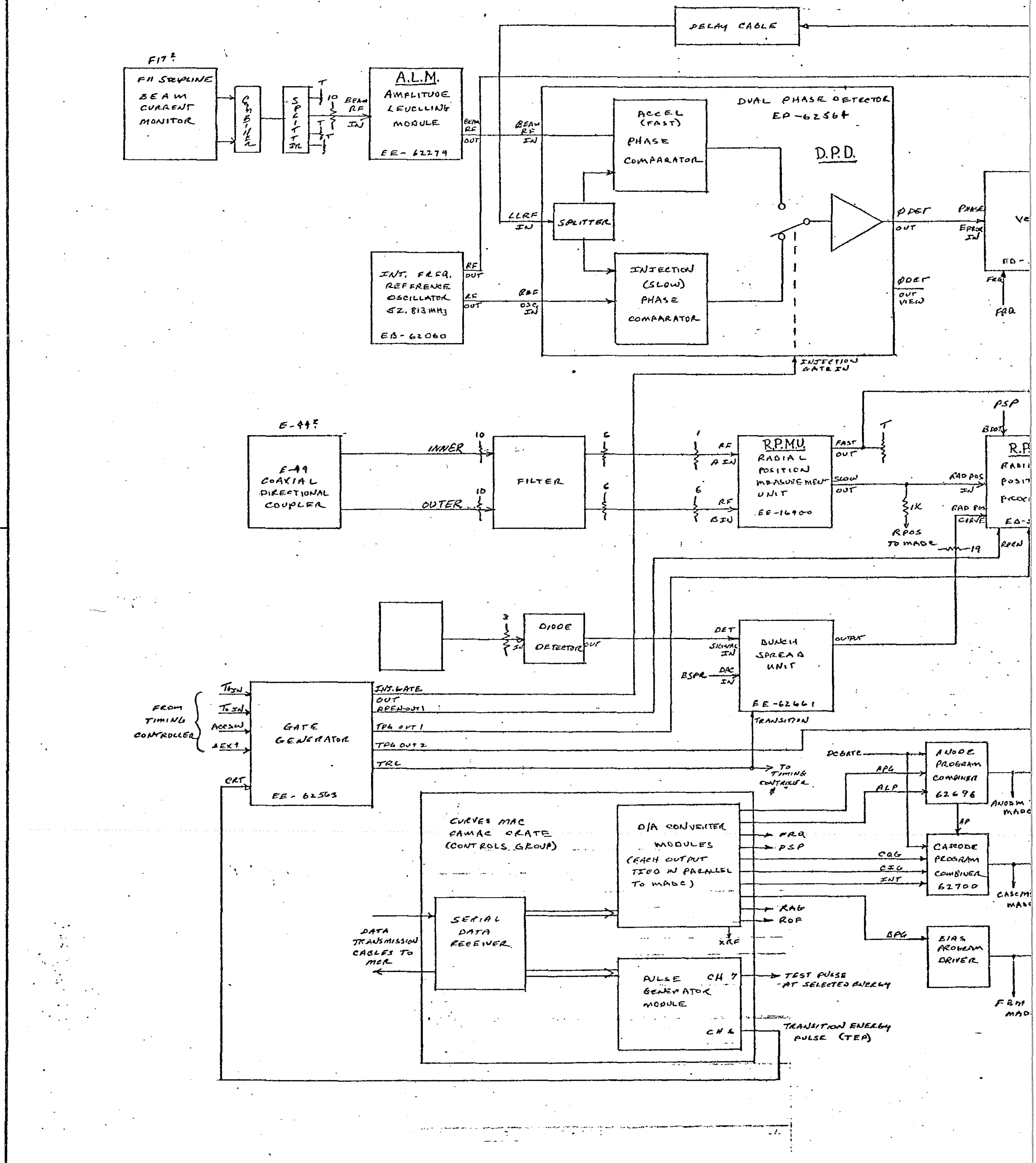
USED ON

MATERIAL-

FERMI NATIONAL ACCELERATOR LABORATORY
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

MAIN RING RF LOW LEVEL SYSTEM BLOCK DIAGRAM

SCALE	FILMED	DRAWING NUMBER


DELAY CABLE
F17
F11 STRIPLINE BEAM CURRENT MONITOR
SPLITTER
A.L.M.
AMPLITUDE LEVELLING MODULE
EE-62279
BEAM RF IN
BEAM RF OUT
DUAL PHASE DETECTOR
ED-62564
D.P.D.
ACCEL (FAST) PHASE COMPARATOR
SPLITTER
LLRF IN
INJECTION (SLOW) PHASE COMPARATOR
REF OSC IN
ϕ DET OUT
ϕ DET OUT VIEW
INJECTION GATE IN
INT. FREQ. REFERENCE OSCILLATOR 52.813 MHz
EB-62060
RF OUT
PHASE ERROR IN
FRQ
E-44
E-44 COAXIAL DIRECTIONAL COUPLER
INNER
OUTER
FILTER
R.P.M.U.
RADIAL POSITION MEASUREMENT UNIT
EE-16900
RF A IN
RF B IN
FAST OUT
SLOW OUT
1K
RPOS TO MADC
PSP
BOOT
RAD POS IN
RAD POS CURVE
RPEN
DIODE DETECTOR
DET SIGNAL IN
DAC IN
BSPR
BUNCH SPREAD UNIT
EE-62661
OUTPUT
TRANSITION
FROM TIMING CONTROLLER
GATE GENERATOR
EE-62563
INJ. GATE OUT
RPEN-OUT
TPG OUT 1
TPG OUT 2
TRL
CRT
TO TIMING CONTROLLER
DCGATE
APG
ALP
ANODE PROGRAM COMBINER 62696
ANODE MADC
AP
CASCODE PROGRAM COMBINER 62700
CASCODE MADC
CGG
CIG
INT
BPG
BIAS PROGRAM DRIVER
FBM MADC
CURVES MAC CAMAC CRATE (CONTROLS GROUP)
D/A CONVERTER MODULES (EACH OUTPUT TIED IN PARALLEL TO MADC)
FRQ
PSP
RAG
ROF
XRF
SERIAL DATA RECEIVER
DATA TRANSMISSION CABLES TO MCR
PULSE GENERATOR MODULE
CH 7
CH 6
TEST PULSE AT SELECTED ENERGY
TRANSITION ENERGY PULSE (TEP)