Overview of Present TeV BPM
Signal Processing and Thoughts

Bob Webber
8/18/2003

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e for Precision Location of the
n Detectors in the Energy Saver

llas, F. Turkot, R.C. Webber, A. Wehmann
ional Accelerator Laboratory
P.O. Box 500
Batavia, IL 60510

Saver[1]
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2x10^13
ocation
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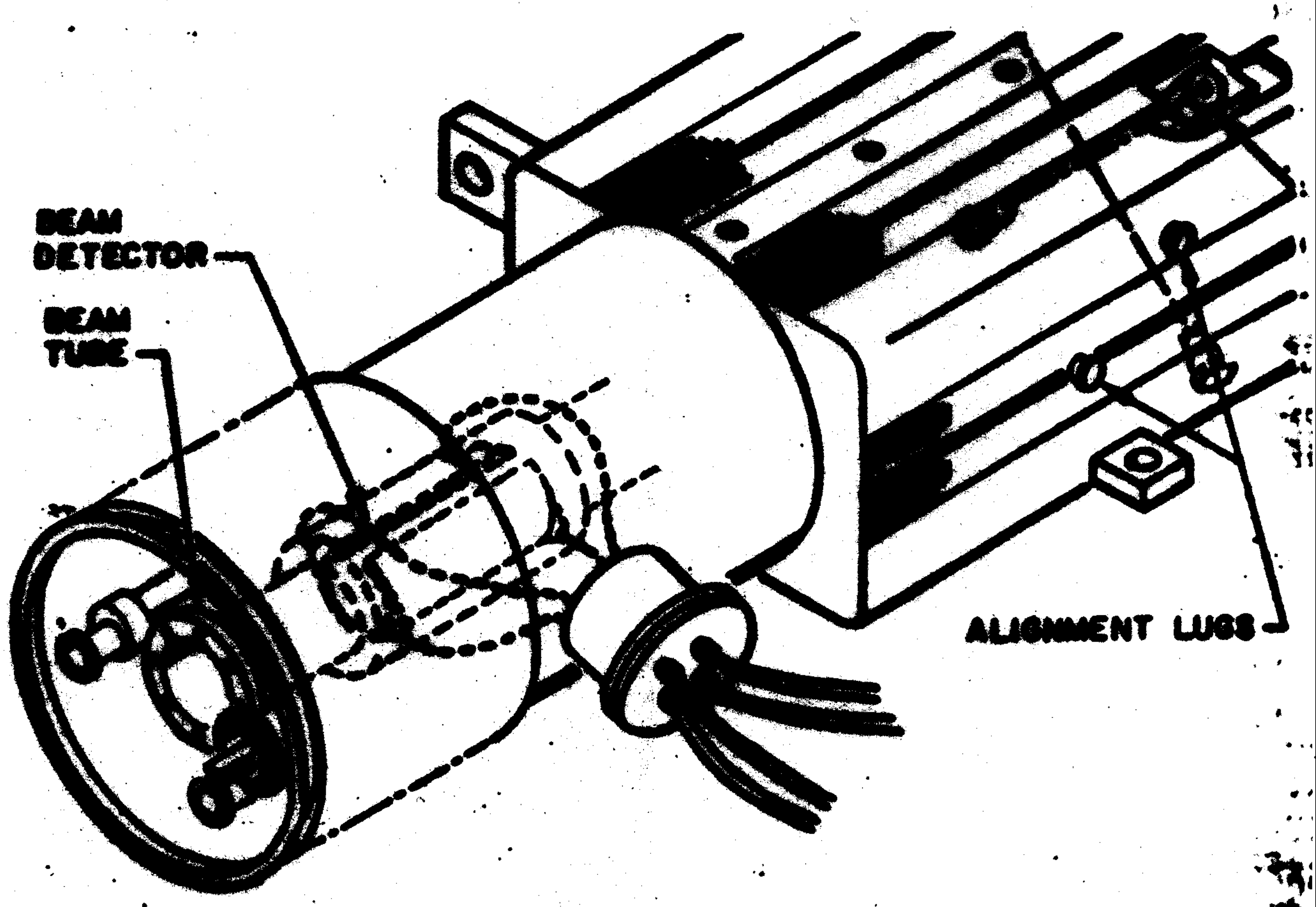
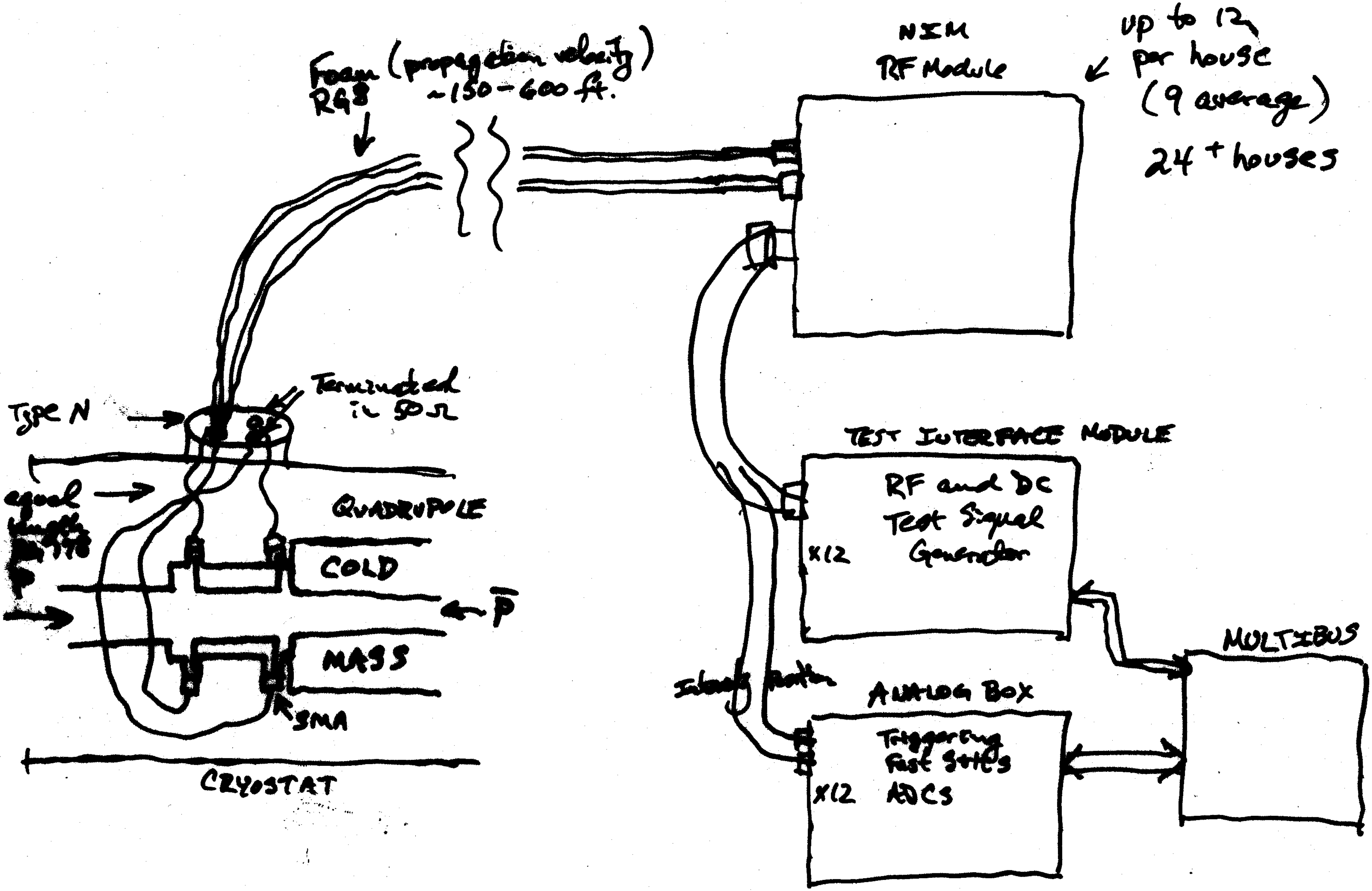


FIGURE I
UPSTREAM END OF QUADRUPOLE SHOWING BEAM DETECTOR ASSEMBLY

matching transformers

TEV BPM LAYOUT



Deep BPM Thoughts

NOTE DATE: 1994

by Bob Webber

I. TEV BPM History - Why it is what it is

A. Motivators

1. commissioning, tune-up (short batch, low intensity), and operation (high intensity slow spill fixed target mode, perhaps eventual colliding beams) of first-ever high energy superconducting magnet synchrotron
2. availability of single turn normalized position information for beam abort system for quench prevention and magnet damage protection
3. manageable cost and complexity resulting in primarily closed orbit system (as opposed to global TBT or position vs. 'time in batch train' system) (resulting in only two selectable delays to sample time following gap in beam)
4. availability of functioning system for initial beam commissioning
5. reliability and maintainability (though not in the most formal sense)

B. Design Goals

1. large 'instantaneous' (no range switching) beam intensity dynamic range
2. short batch to full ring operational capability (single bunch measurement performance was a secondary priority)
3. availability of wide bandwidth, 'real time', normalized position signal for abort system inputs (turned out not to be important, loss monitors are the more useful 'early warning' devices)
4. first pass position and intensity information availability
5. built-in test features (power supply monitoring, cable testing, signal processing testing with built-in beam simulations signals)

TEV was the first machine to have the luxury of being commissioned with a BPM system that had been given appropriate design attention and money sufficiently in advance.

II. SSC BPM Status

A. Few Final Design Decisions Actually Reached

1. combination of diode peak detectors and AM/PM was the baseline signal processing plan for the SSC collider rings

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2. this was not a satisfactory, suitable, nor complete plan
3. enormous work remained to be done to specify BPM system of agreed up performance capability

B. Committed to utilization of log amp circuitry for Linac and LEB

1. confident of suitability for those applications
    a) sufficient prototyping and testing had been done (even in FNAL Booster)
    b) performance requirements for these machines were not too tough
2. experience of those applications was needed before finalizing decision for superconducting rings
3. sum and difference nomenclature got perverted in some of the write-ups

III. Persistent BPM Problems

A. Range of beam charge distributions and magnitudes to be accommodated (number of bunches, bunch length, repetition frequency, etc.)

B. Timing

1. 'self-triggering' always has problems with bunch/batch intensity, charge distribution, and bunch/batch shape variations
2. external triggering is expensive in large distributed systems

C. A and B (or equivalent) Channel Matching

1. stability vs. time and temperature
2. tougher with larger signal dynamic range

We signal tested, temp tested, and matched or pair-selected a large fraction of the components in all TEV/MR style BPM RF Modules.

3. on-line calibration may help
    a) calibration system and signal injection paths must overcome same time/ temp sensitivities and problems
    b) calibration system may also be inadequate or erroneous (as in LEP where calibration pulse shape and frequency content did not adequately replicate beam pulse leading to erroneous calibration, machine operational confusion, and eventually expensive retro-fit)

IV. My General Concerns

A. With fast 'bunch sampling' schemes

1. sample trigger accuracy (see TIMING above)

a) channel to channel

b) vs. time and temp

c) vs. beam intensity

d) vs. bunch shape

2. dynamic range

3. accuracy and noise of sampling circuitry

B. With 'normalization after digitization'

1. limited instantaneous dynamic range (range switching usually required)

2. absence of availability of low latency normalized analog signal

Concerns can be alleviated with proper specification of BPM system performance requirements and with suitable understanding of the compromises that are possible or may be necessary.

Systems specifiers and designers are well served to appreciate the differences between measurement of beam parameters (single pass position, position vs. time in a batch or train of batches, oscillation amplitude, instability modes, energy error, etc.) and measurement of machine parameters (closed orbit, tune, dispersion, chromaticity, phase advance, β function, etc.) BPM systems are nearly always called upon to serve both needs. Most of the beam parameters are global and may be determined by measurement at one or a small number of locations in a ring. Many of the machine parameters, closed orbit for example, are local and require measurement at a large number of locations for complete information. An understanding of these differences is essential to making satisfactory compromises when lack of time, money, people, or whatever prevent design of the perfect, all encompassing system.

V. Amazements of a BPM Designer

A. How much unquestioning faith users put in BPM data under all conditions if the system is shown to work well in one instance.

B. How a system with so many shortcomings can still serve so well.

C. How much more difficult are the design/implementation/operational problems of the control systems/user interface than the so 'agonized about' analog signal processing problems.

D. How a beautiful signal processing scheme can simply be an inconsequential

part of a miserable BPM system when the user interface is screwed up.

E. How every BPM system is expected to everything, in spite of what it was designed to do.

F. How the beam always ends up being configured to produce signals just on the edge of what the BPM system was designed to handle.

G. How difficult it is to reach necessary decisions to limit the scope of performance of a BPM system in specification.

VI. The Ideal System

A. Reliable External Triggering

B. Wideband Analog Normalization

C. Turn - by - Turn Digitization with Deep Memory

D. Sufficiently Large Instantaneous Dynamic Range

E. Designed-in and built-in time and temperature stability

Design compromises always will be necessary. The best design will depend on the particular application and that best design may have to be compromised. The attempt to apply the Tevatron Multibus based system to the Main Ring, to transfer lines, to P-bar, and then to Booster resulted in progressively less satisfactory performance. This was the result of a compromise in which the motivation to apply existing hardware won out over the desire for optimal performance.

The signal processing circuitry and the control system/user interface are quite separate aspects of a BPM system, but the system will be most acceptable only when those two complement each other by design and the important performance objectives of the system are limited and understood from the start.

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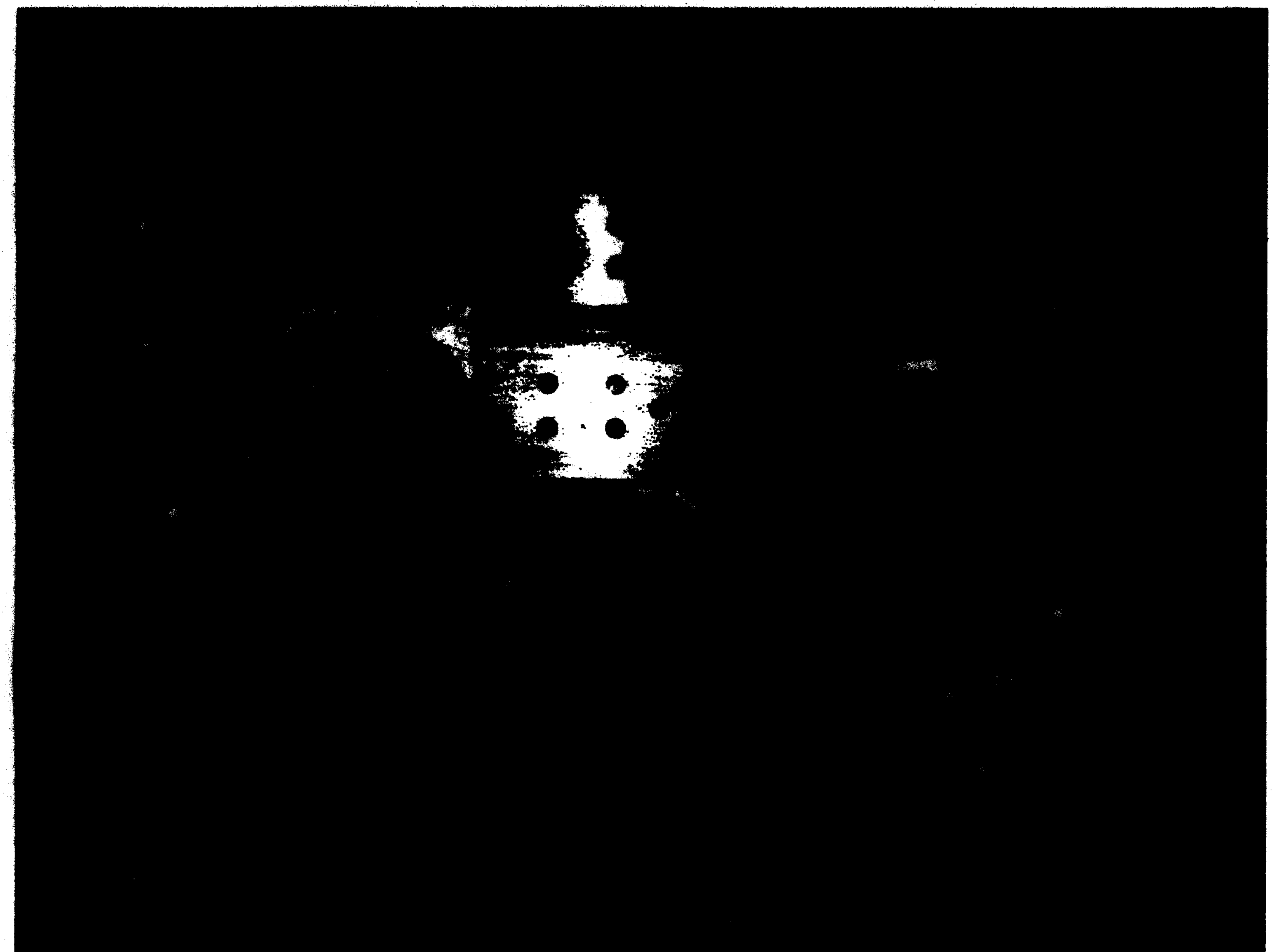
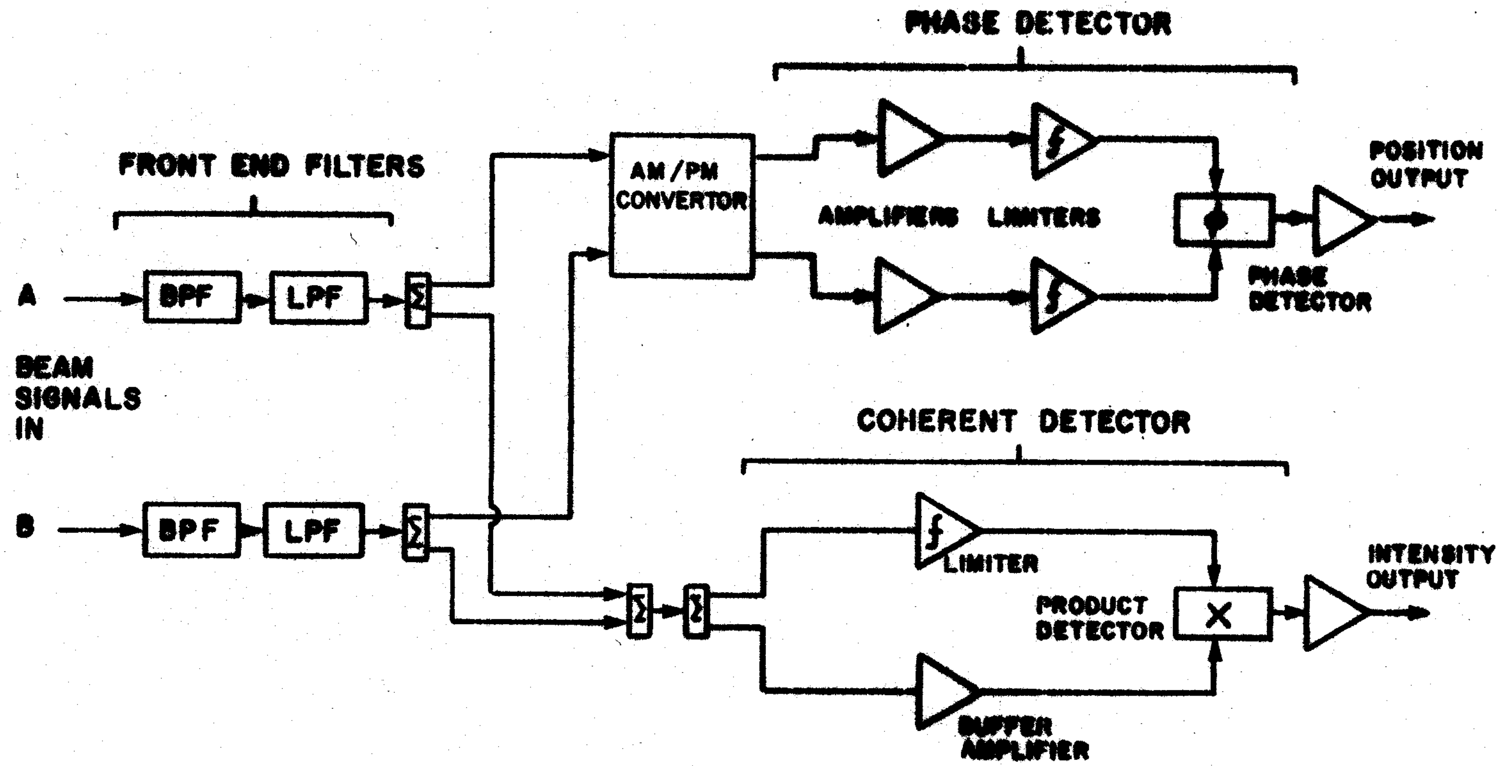
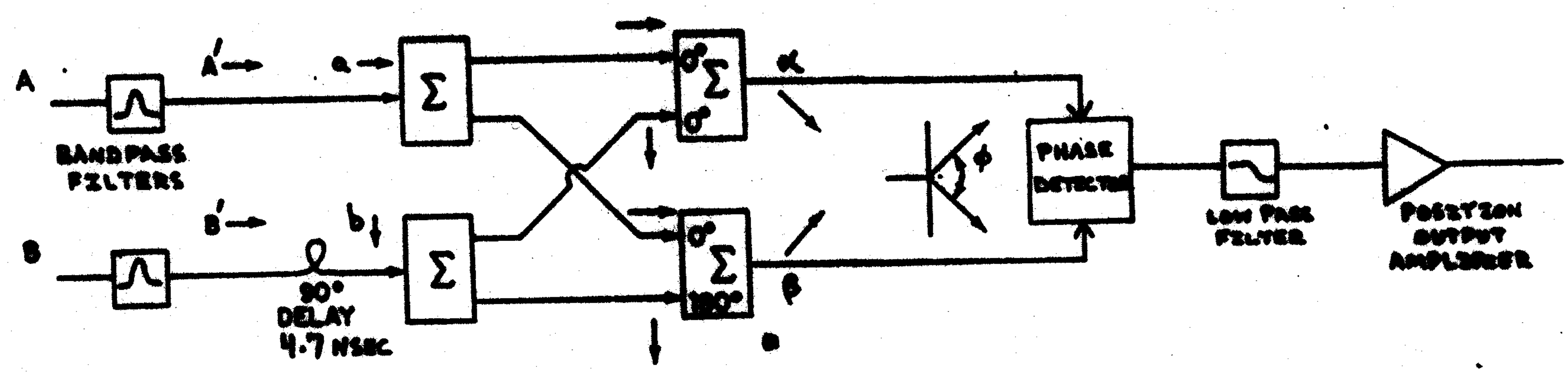
TeV BPM RF Module



0 4.25"



FERMI TEVATRON ELECTRONICS



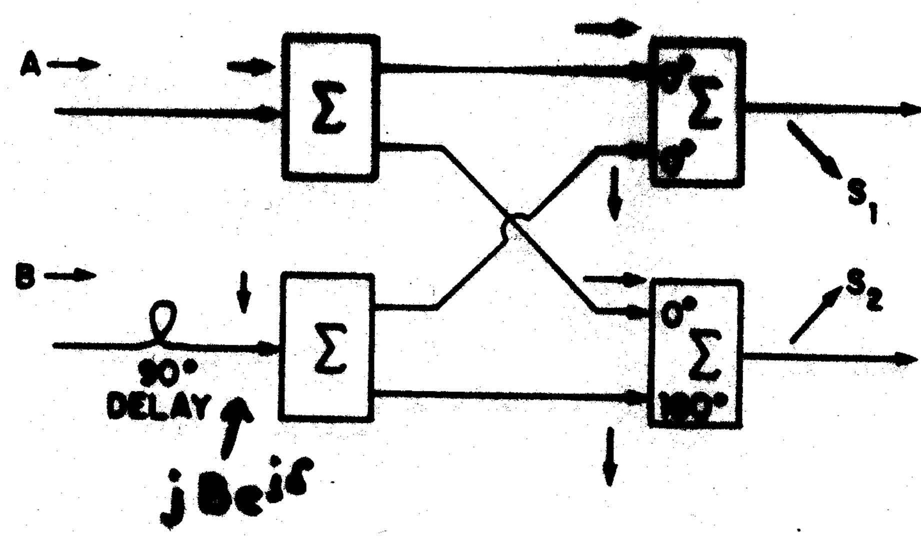
RF MODULE POSITION CHANNEL BLOCK DIAGRAM

FIGURE 1

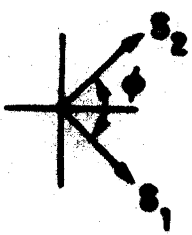
AM-PM Transfer Function

A

$Be^{j\delta}$



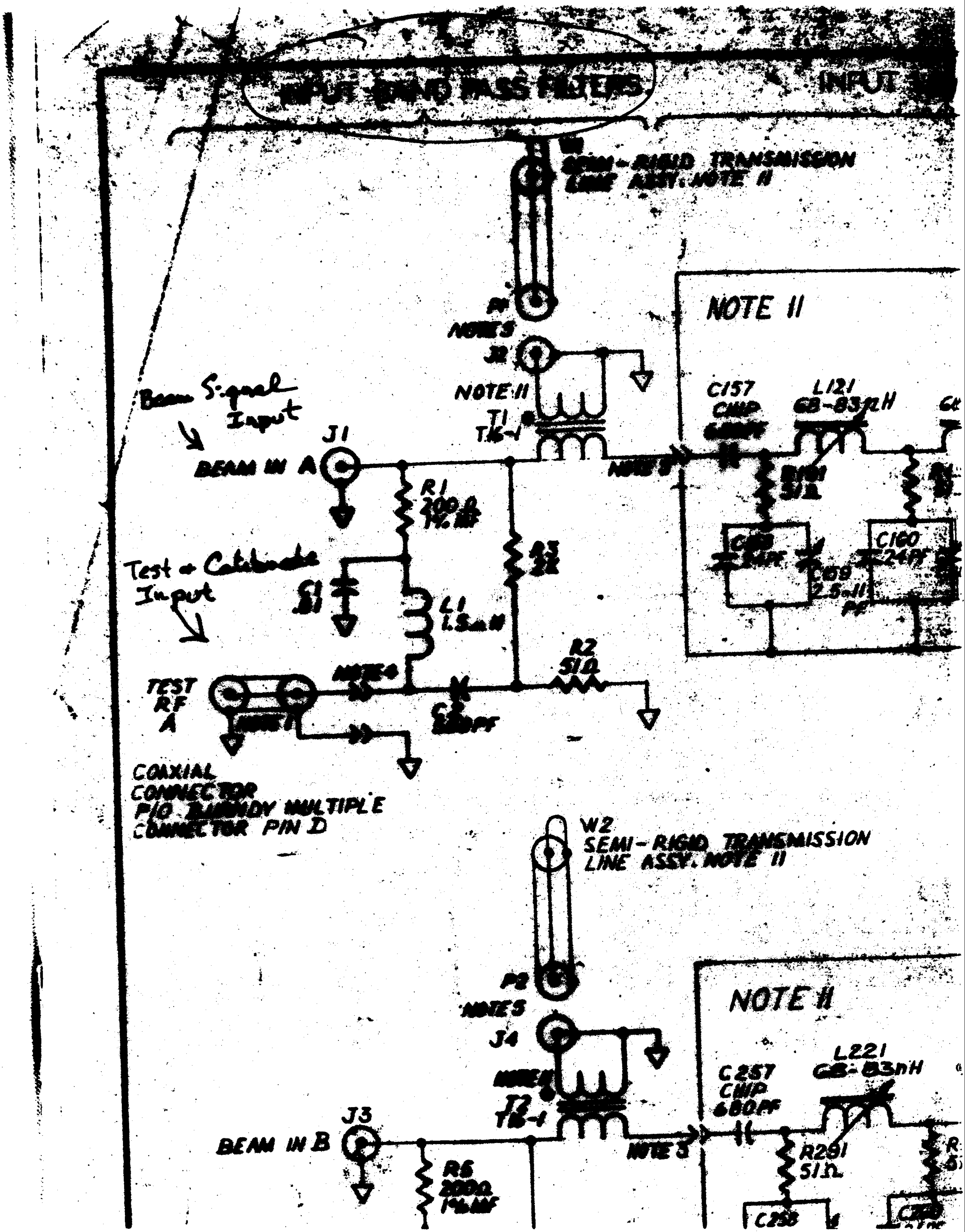
$\frac{A}{2} + j\frac{B}{2}e^{j\delta} = \frac{A}{2} - \frac{B}{2}\sin\delta + j\frac{B}{2}\cos\delta$



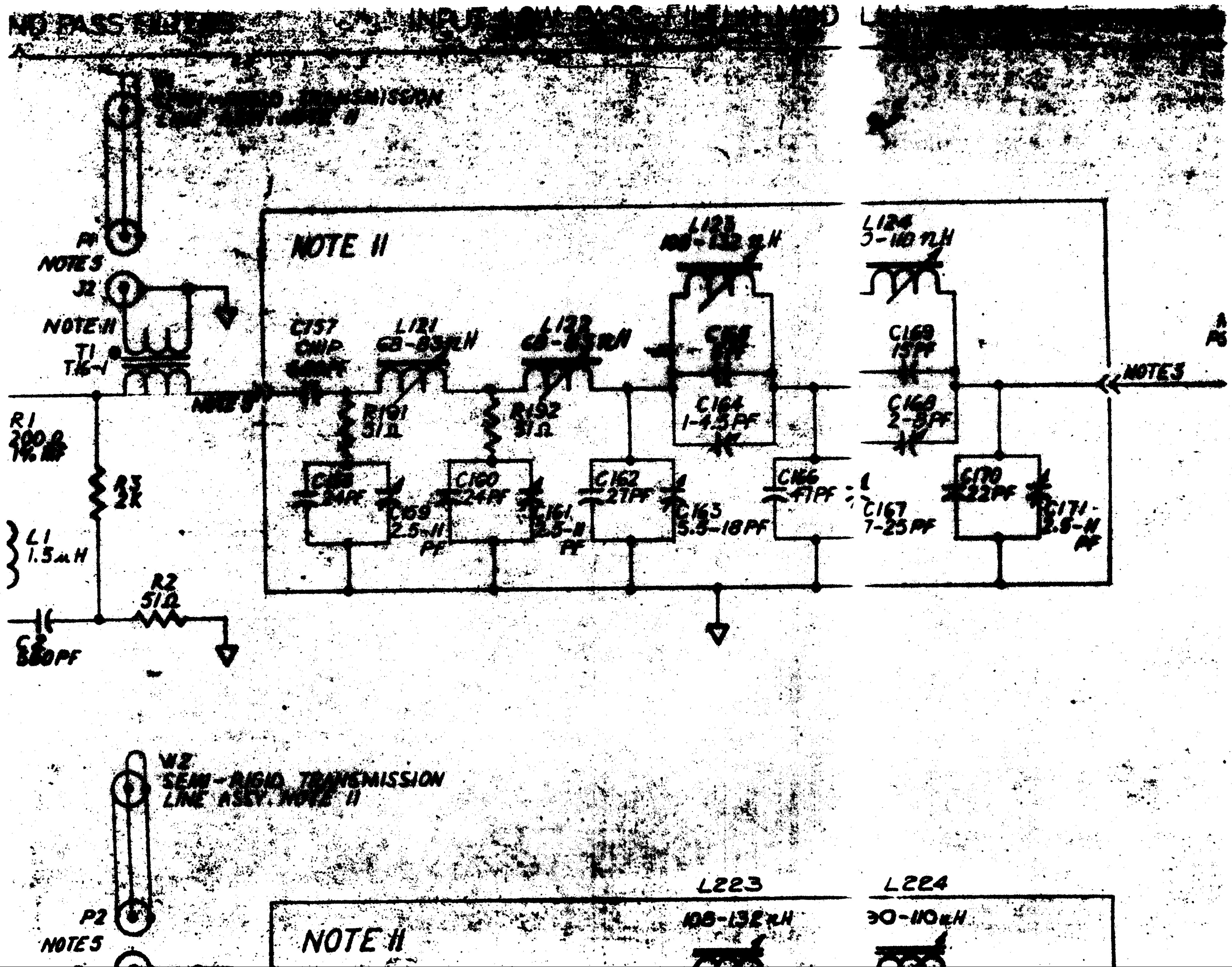
$\frac{A}{2} - j\frac{B}{2}e^{j\delta} = \frac{A}{2} + \frac{B}{2}\sin\delta - j\frac{B}{2}\cos\delta$

$$\phi = \arctan\left[\frac{\frac{B}{2}\cos\delta}{\frac{A}{2} - \frac{B}{2}\sin\delta}\right] - \arctan\left[\frac{-\frac{B}{2}\cos\delta}{\frac{A}{2} + \frac{B}{2}\sin\delta}\right]$$

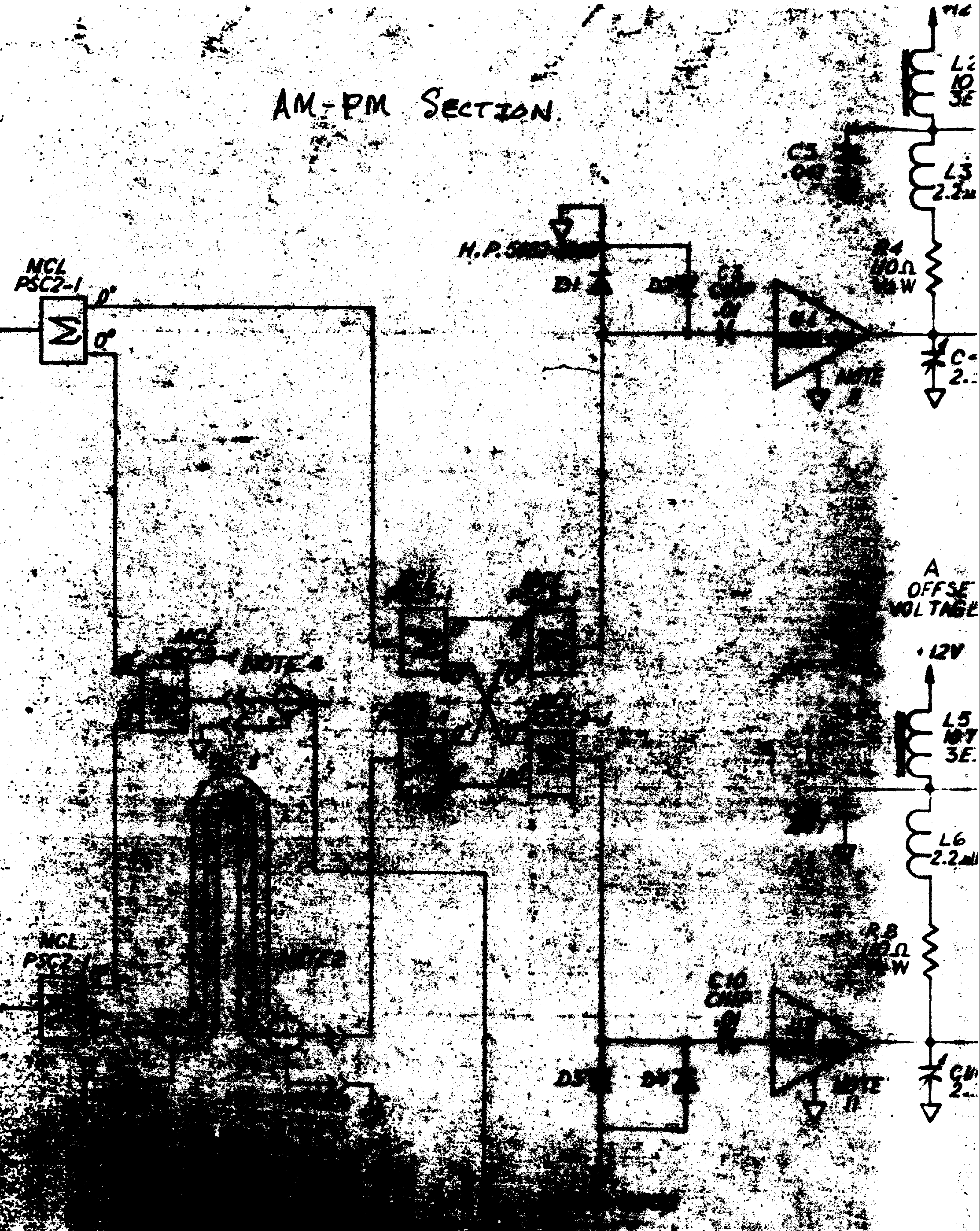
for $\delta = 0$ $\quad \phi = 2\arctan\frac{B}{A}$

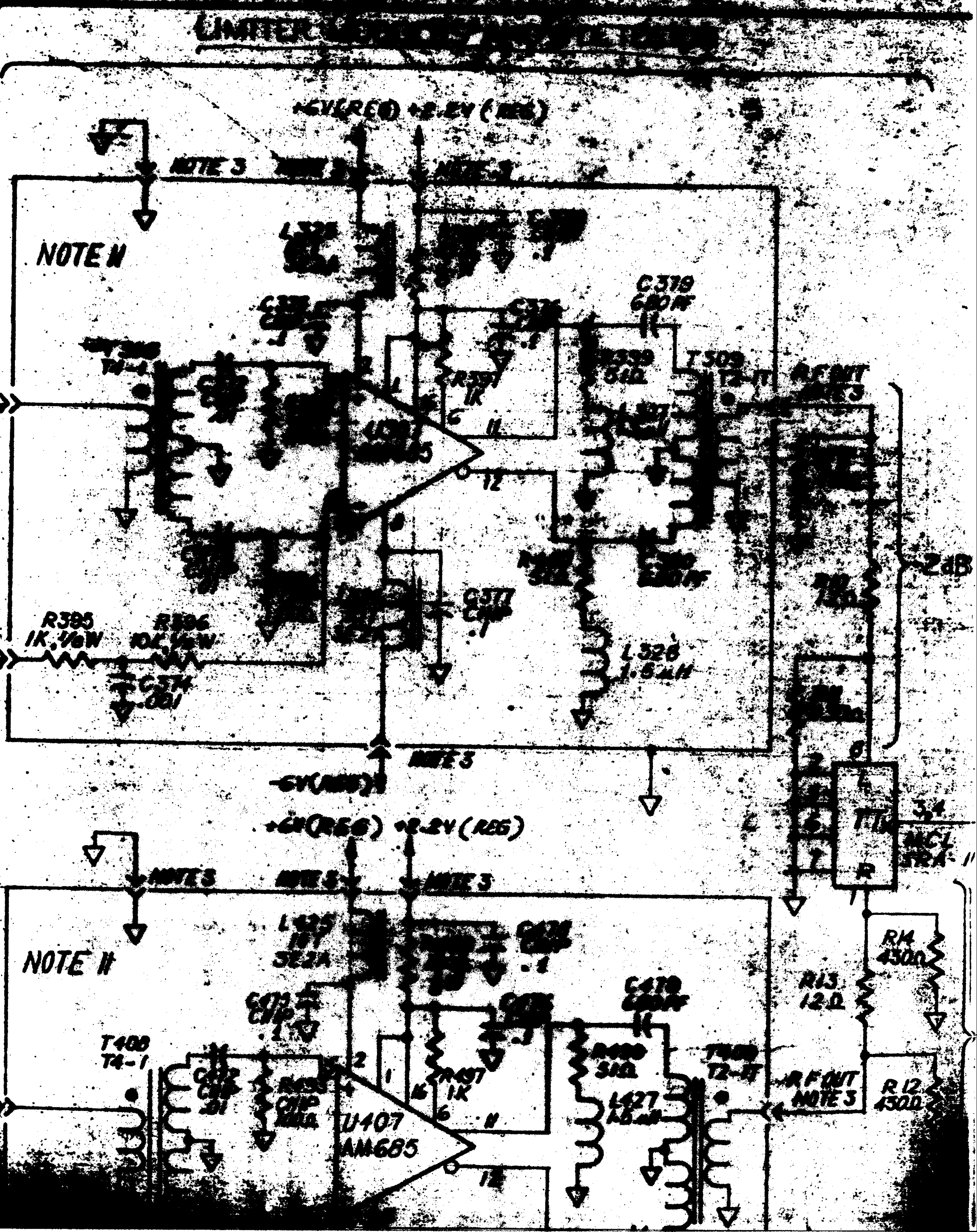


INPUT BAND PASS FILTERS
INPUT
SEMI-RIGID TRANSMISSION LINE ASSY. NOTE 11
NOTE 11
NOTE 5
NOTE 11
C157 CHIP
L121 68-83nH
Beam Signal Input
J1
BEAM IN A
R1 200Ω 1%
T1 T16-1
R3 3K
Test or Calibrate Input
L1 1.5uH
R2 51Ω
C100 24PF
TEST RF A
COAXIAL CONNECTOR P/O MULTIPLE CONNECTOR PIN D
W2 SEMI-RIGID TRANSMISSION LINE ASSY. NOTE 11
P2
NOTE 5
J4
NOTE 11
T2 T16-1
L221 68-83nH
C257 CHIP 680PF
J3
BEAM IN B
R6 200Ω 1%
NOTE 3
R291 51Ω
C258

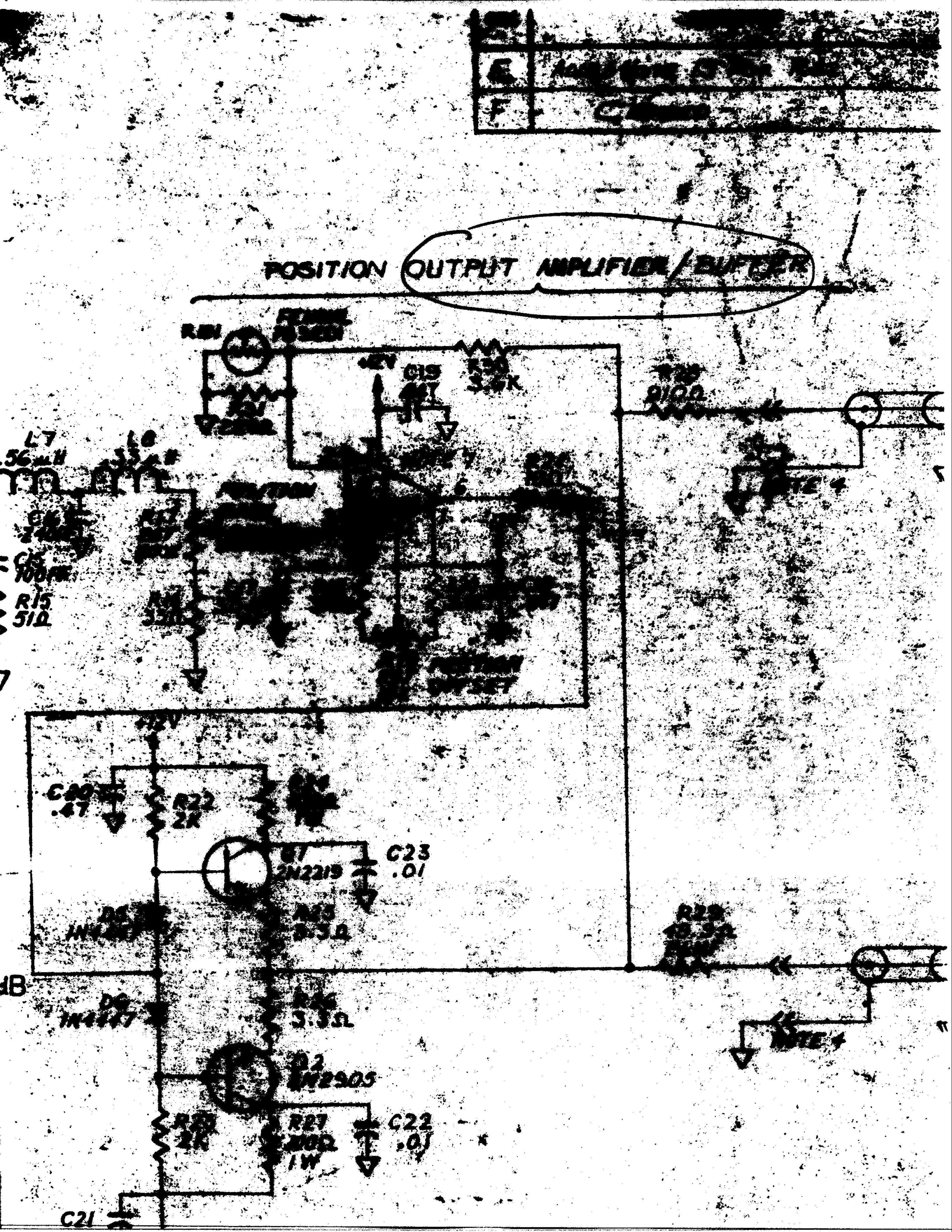

NOTE 11
P1
NOTES
J2
NOTE 11
T1
T16-1
C157
CHIP
L121
68-83 nH
R101
51Ω
L122
R102
51Ω
L123
L124
3-110 nH
C169
15PF
C168
2-3PF
C164
1-4.5PF
C160
24PF
C159
2.5-11 PF
C161
2.5-11 PF
C162
27PF
C163
5.5-18PF
C166
47PF
C167
7-25PF
C170
22PF
C171
2.5-11 PF
NOTES
R1
200 Ω
R3
2K
L1
1.5 uH
R2
51Ω
C2
880PF
W2
SEMI-RIGID TRANSMISSION
LINE ASSY. NOTE 11
P2
NOTES
NOTE 11
L223
108-132 nH
L224
30-110 nH

AM-PM SECTION.





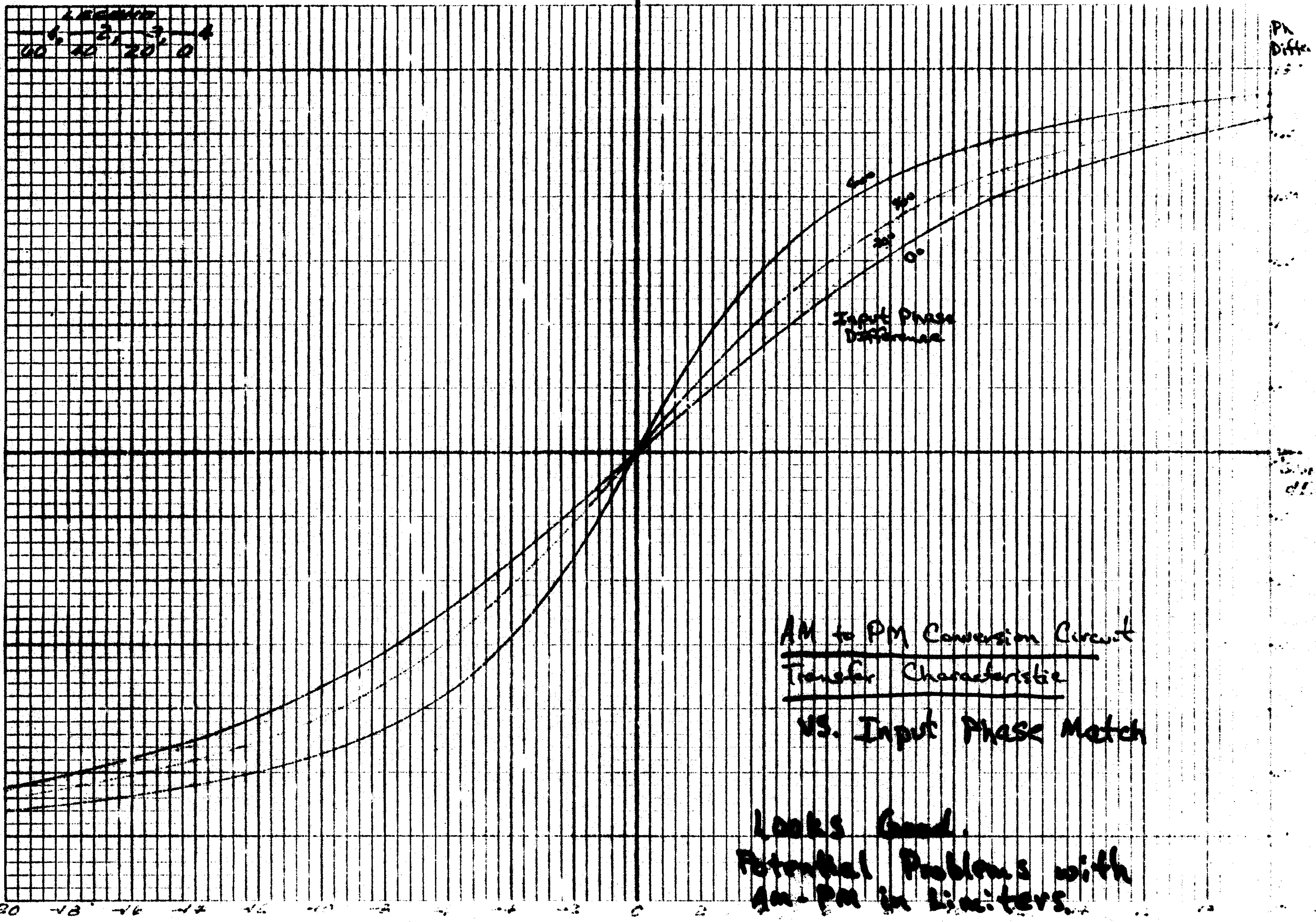
NOTE 3
NOTE 11
+8.2V (REG)
C 378
680 PF
R 391
1K
T 309
T2-1T
2dB
R395
1K 1/8W
R396
10K 1/8W
L 328
1.5 µH
-6V (REG)
+6V (REG)
+8.2V (REG)
L 425
C 478
680PF
R 407
1K
T408
T4-1
U 407
AM685
R F OUT
NOTE 3
R14
430Ω
R13
12Ω
R 12
430Ω
3,4
MCL
SRA-1


E
F
POSITION OUTPUT AMPLIFIER/BUFFER
3.4K
C19
L7
.56uH
C15
100pF
R15
51Ω
+12V
C20
.47
R22
2K
2N2219
C23
.01
3.3Ω
dB
D6
1N4447
2N2905
R27
100Ω
1W
C22
.01
2K
C21
NOTE 4

K+E 5 X 5 TO 1/2 INCH • 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A. 46 0860

BMAG vs. ΔΦ (CORRECTED)

R CLIFF 10/16/80



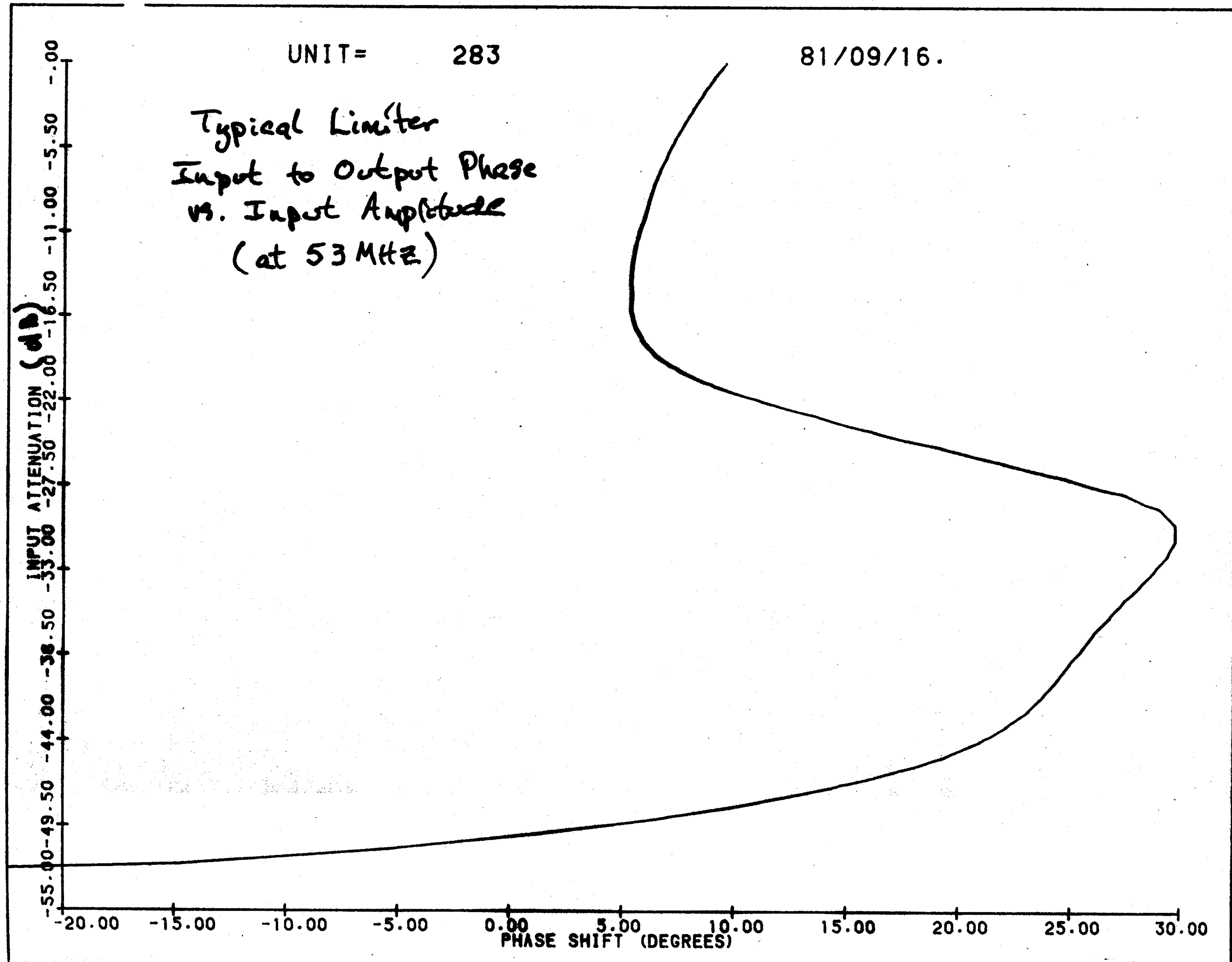
AM to PM Conversion Circuit

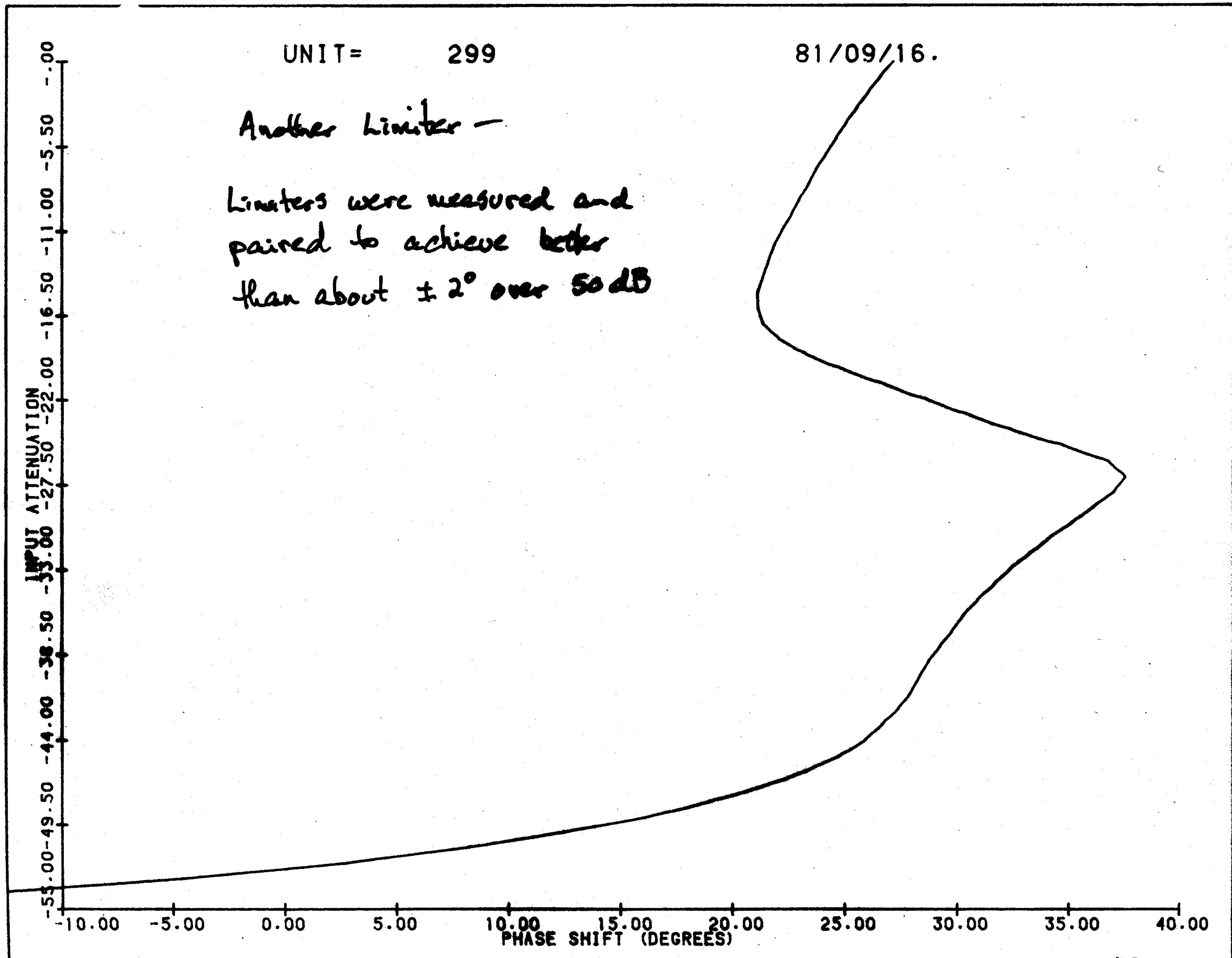
Transfer Characteristic

VS. Input Phase Match

Looks Good.

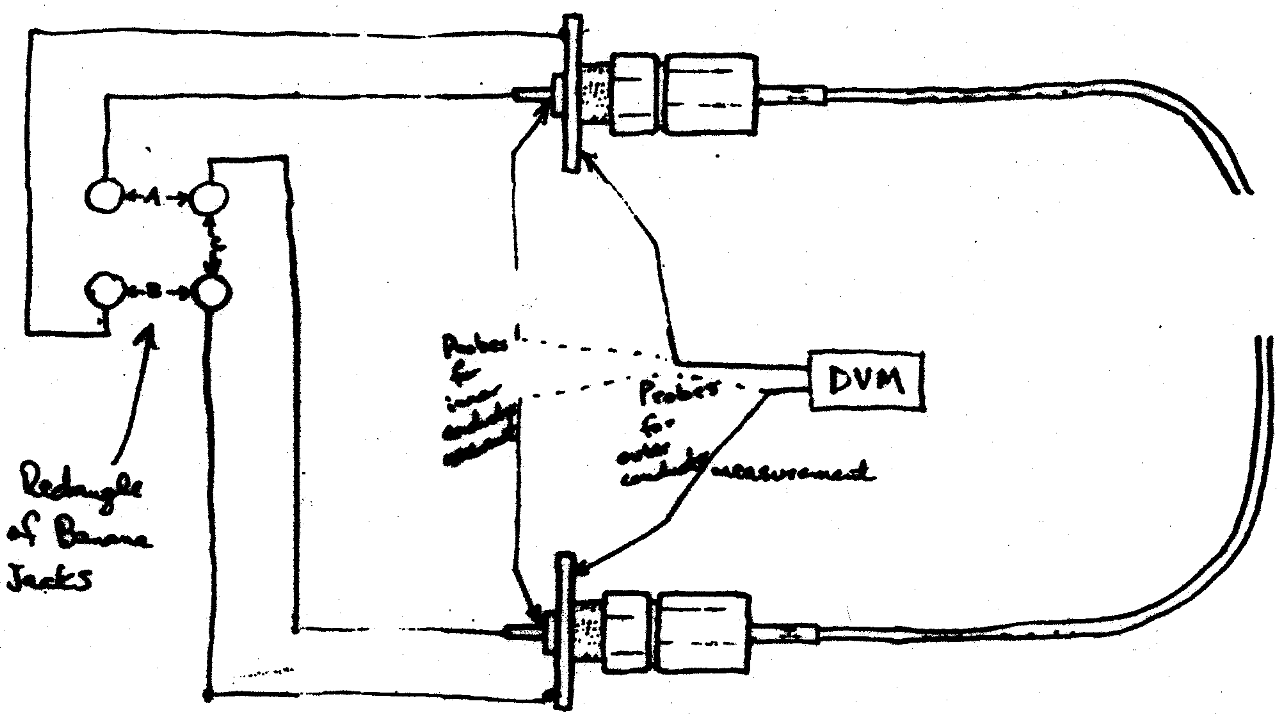
Potential Problems with AM-PM in Limiters.


UNIT= 283
81/09/16.
Typical Limiter
Input to Output Phase
vs. Input Amplitude
(at 53 MHz)
INPUT ATTENUATION (dB)
-.00
-5.50
-11.00
-16.50
-22.00
-27.50
-33.00
-38.50
-44.00
-49.50
-55.00
-20.00
-15.00
-10.00
-5.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
PHASE SHIFT (DEGREES)


UNIT= 299
81/09/16.
Another Limiter —
Limiters were measured and
paired to achieve better
than about ± 2° over 50 dB
INPUT ATTENUATION
-.00
-5.50
-11.00
-16.50
-22.00
-27.50
-33.00
-38.50
-44.00
-49.50
-55.00
-10.00
-5.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
PHASE SHIFT (DEGREES)

CABLE RESISTANCE TEST FIXTURE

Quality Measurements of RG178 Cable / Connector Sections

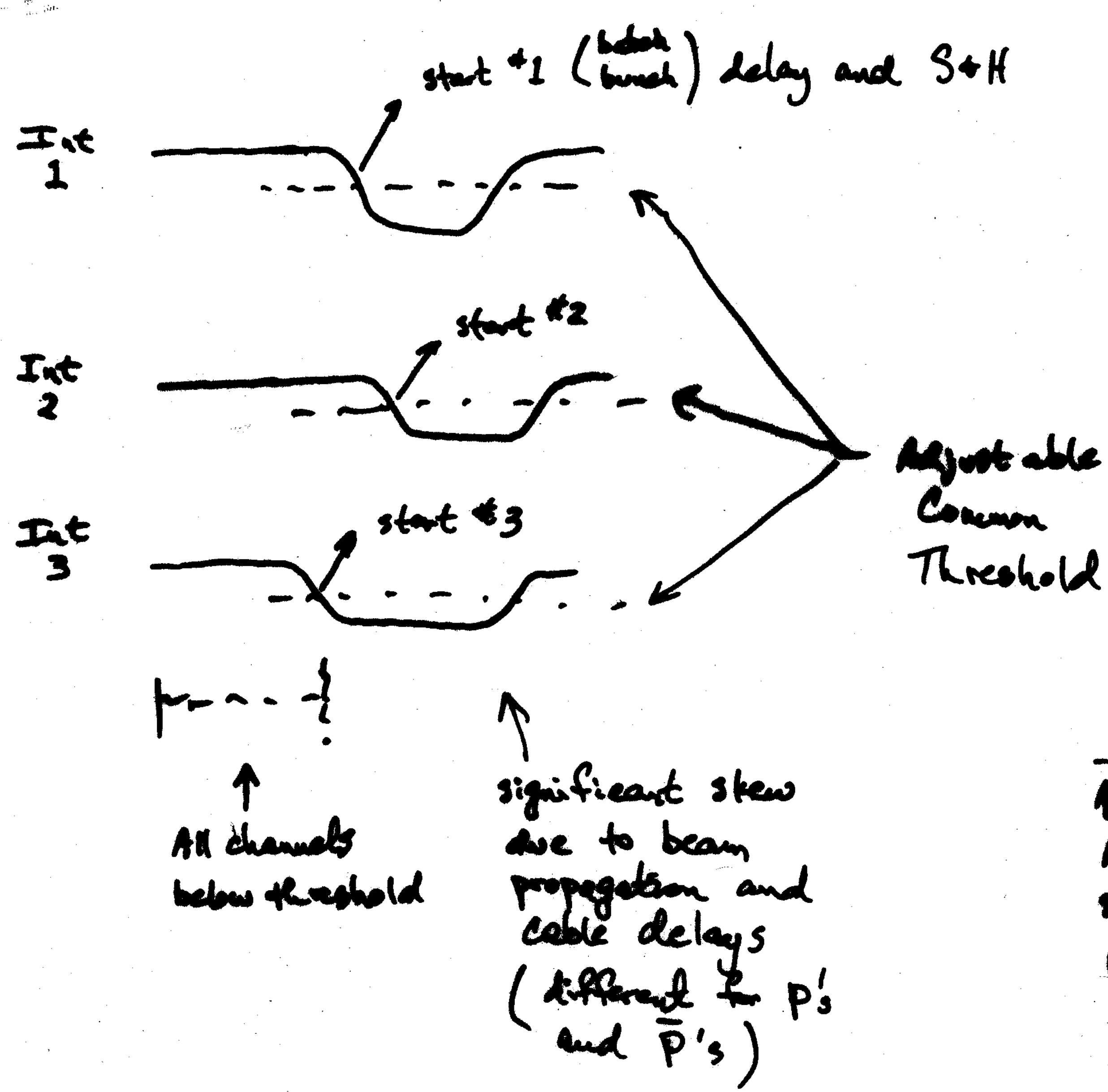


A - current connections for center conductor measurement

B - current connections for outer conductor measurement

C - voltage connections for hi-pot test

Timing And Triggering in Analog Box



~ SEQUENCE ~

All channels below threshold
ARM
start S+H delay (batch ~ ½ μsec, bunch ~ 200 ηsec)
hold → begin hold off (fraction of turn)
digitize
Re-arm when all channels below threshold

BPM DESIGN NOTE #26

A CLOSER LOOK AT RF MODULE AND DAUGHTER CARD RESPONSE TO SHORT BATCH AND SINGLE BUNCH BEAM SIGNALS

ROBERT C. WEBBER
JANUARY 8, 1988

This report describes the results of recent efforts to better understand how to interpret and best sample the position signals from Main Ring and Saver style Beam Position Monitoring systems. An inherent dynamic error in the AM/PM circuit implementation, limitations imposed by settling time of the RF Module position output amplifier, and criteria for determining optimal daughter card track and hold gate widths are discussed.

DYNAMIC ERRORS IN THE RF MODULE

A systematic dynamic effect in the expected output of the RF Modules is now understood. The effect is the result of differential delays in the A and B signal channels in the module; in particular, an intentional 4.7 nanosecond delay in the B channel. See Figure 1 for a block diagram of the RF Module position channel. This delay causes position output errors whenever the inputs are not in a steady state condition. Steady state is measured on the scale of a time constant equal to 3 to 4 53 Mhz cycles, determined by the bandwidth of the bandpass filter at the RF Module input.

An approximation to this dynamic error can be made as follows. For steady state conditions the phase between the two outputs of the AM/PM converter is

$$\phi = \arctan\left(\frac{A}{B}\right)$$

where A and B are the amplitudes of the input signals.

The output of the phase detector is then

$$V_{pd} = K\left(\frac{\pi}{2} - \phi\right)$$

The envelope burst of RF at the output of the bandpass filters can be described as

$$A' = A\left(1 - e^{-t/\tau}\right)$$

$$B' = B\left(1 - e^{-t/\tau}\right)$$

where τ is the envelope risetime of the filters. τ = 66 nsec in the MR/Saver RF Modules. See Photograph 1. Because of the 4.7 nsec delay, the initial α and β signals have no contribution from signal B. This is equivalent to beam being all the way out on the A side of the pick-up. After the delay, some signal from B begins to contribute, but because of the finite risetime of the envelope, the B contribution never quite catches up to that of A. Once B begins to contribute, the relative envelopes into the combiner, until the end of the burst, are

$$a = A \left[1 - e^{-t/\tau}\right]$$

$$b = B \left[1 - e^{-(t-d)/\tau}\right]$$

$$\phi = 2 \arctan \left[\frac{A\ (1 - e^{-t/\tau})}{B\ (1 - e^{-(t-d)/\tau})}\right] =$$

$$2 \arctan \left[\frac{A\ (1 - e^{-t/\tau})}{B\ (1 - 1.074 e^{-t/\tau})}\right]$$

where d=4.7 nsec is the delay time.

After one time constant, find

$$\phi = 2 \arctan \left[\frac{1.04A}{B}\right]$$

After two,

$$\phi = 2 \arctan \left[\frac{1.01A}{B}\right]$$

After many,

$$\phi \rightarrow 2 \arctan \left[\frac{A}{B}\right]$$

At the end of the burst, the reduction of the A contribution leads that of B and the signals are

$$a = A\ e^{-t/\tau}$$

$$b = B\ e^{-(t-d)/\tau}$$

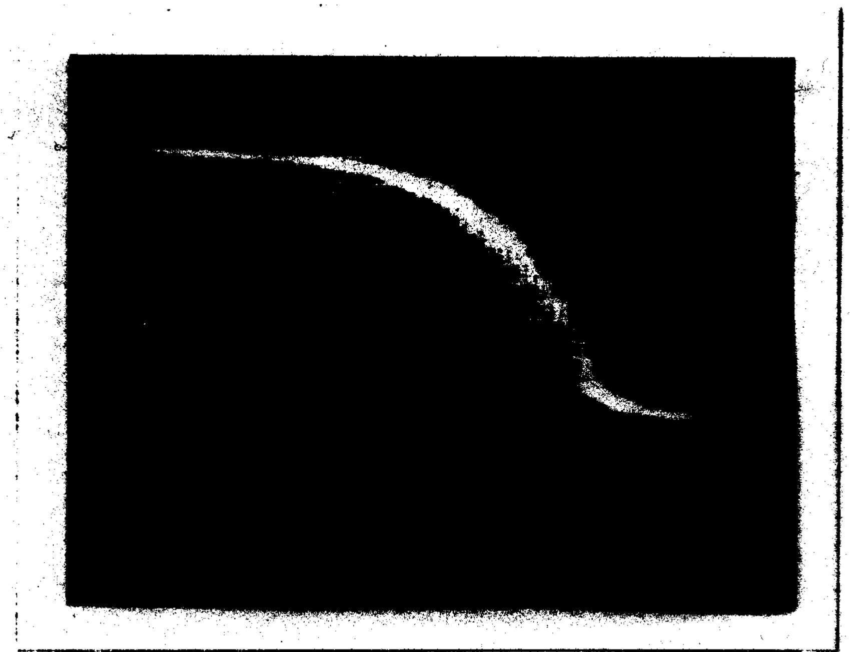
Hence

$$\phi = 2 \arctan \left[\frac{A}{B e^{d/\tau}}\right] = 2 \arctan \left[\frac{A}{1.074B}\right]$$

constant error

Note that this differs from the steady state answer by a fixed factor for ALL TIME (assuming exponential signal decay). The error is determined by $e^{d/\tau} = 1.074$. Note that the error in either case is largest when A=B and goes to zero for A>>B and B>>A.

Actual position signals in an RF Module in response to a burst are shown in Photographs 2 and 3. The initial negative transients are a remnant of the "beam all the way to one side" initial response. The positive steps, appearing when the rf envelope begins to decay, show the "constant error" response. The position traces become wild as actual decaying rf signal levels approach threshold levels of the comparator limiters in the RF Module.

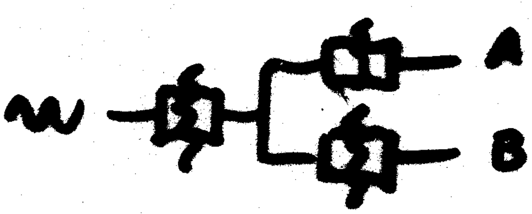


"Position"
1db/trace

-30 dbm

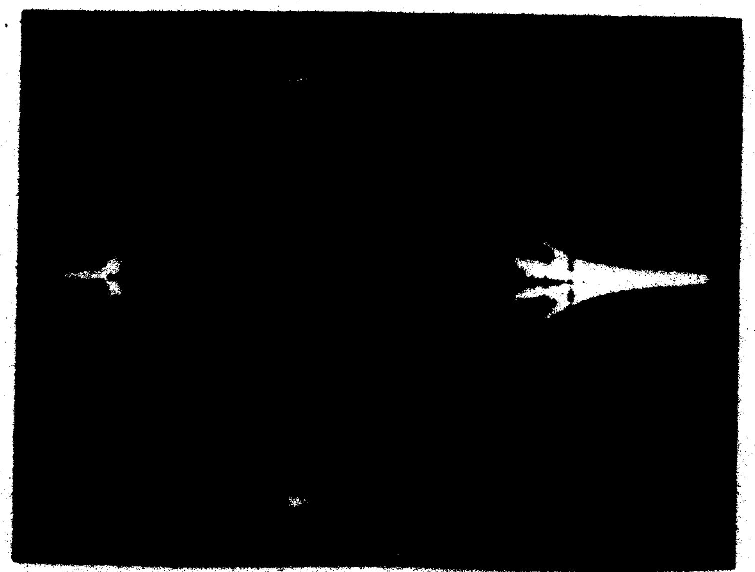
+24 dbm

[illegible] Signal Levels
1 db/step



10 μsec
dwell

SAVER RF MODULE FULL SCAN

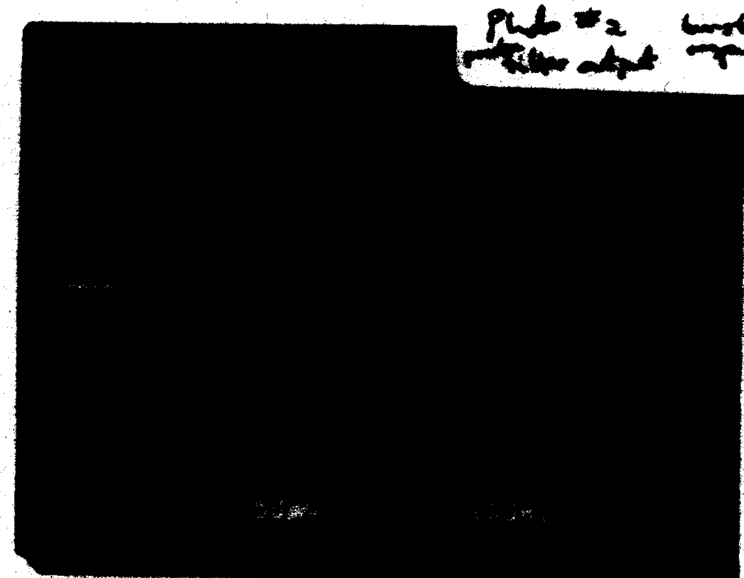


MAIN RING / SAVER RF MODULE FRONT-END FILTER RESPONSE TO ≈ 600 nSEC BURST OF 53 MHZ RF

≈ 66 nSEC TIME CONSTANT

PHOTOGRAPH #1

Photo #2 burst



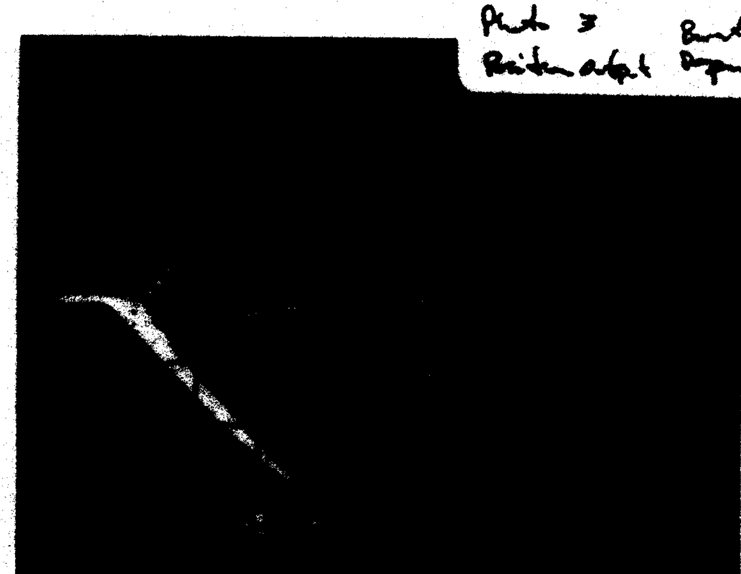
POSITION SIGNALS IN RF MODULE IN RESPONSE TO BURST INPUT

SIGNALS AT PHASE DETECTOR LOW PASS FILTER OUTPUT

NOTE: INITIAL NEGATIVE TRANSIENT AND POSITIVE STEP AS RF ENVELOPE DECAYS

PHOTOGRAPH #2

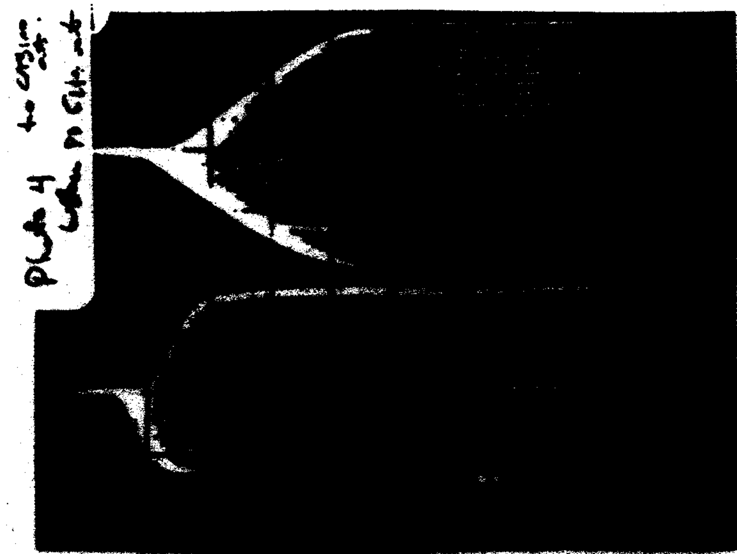
Photo 3 Burst



POSITION SIGNALS AT POSITION AMPLIFIER OUTPUT IN RESPONSE TO BURST INPUT

(END OF BURST NOT SHOWN)

PHOTOGRAPH #3

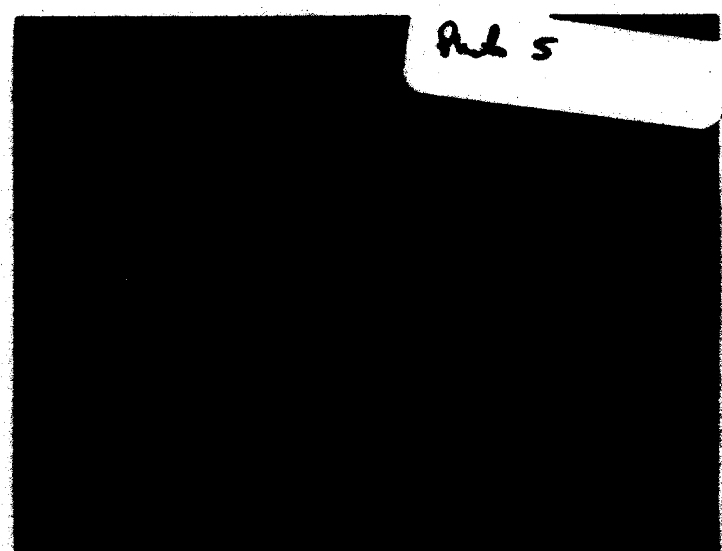


POSITION SIGNALS IN RESPONSE TO FRONT END OF BURST INPUT

TOP - POSITION AMPLIFIER OUTPUT

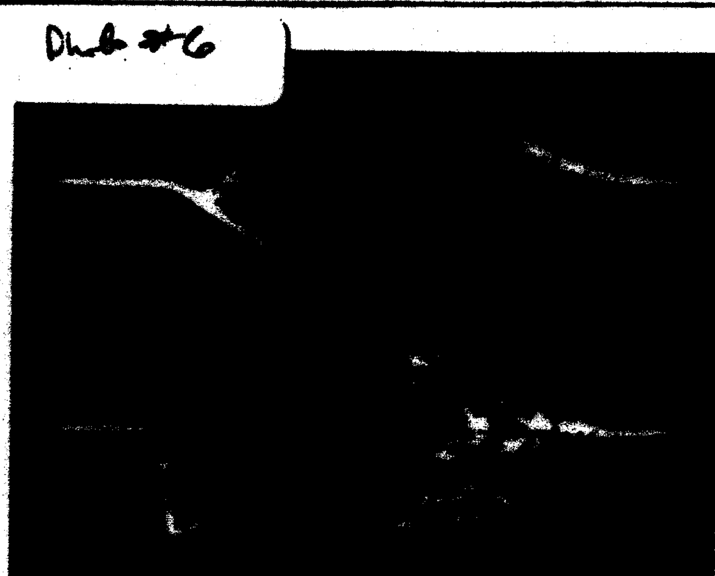
BOTTOM - PHASE DETECTOR LOW PASS FILTER OUTPUT (POSITION AMPLIFIER INPUT)

PHOTOGRAPH #4



FRONT END FILTER RESPONSE TO SINGLE INPUT DOUBLET (SINGLE BUNCH SIGNAL)

PHOTOGRAPH #5



POSITION SIGNALS IN RESPONSE TO SINGLE BUNCH TYPE INPUTS

TOP - POSITION AMPLIFIER OUTPUT

BOTTOM - PHASE DETECTOR LOW PASS FILTER OUTPUT

PHOTOGRAPH #6