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ANTIPROTON SOURCE BEAM POSITION SYSTEM

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I. BPM SYSTEM OVERVIEW

The TeV I Beam Position Monitor (BPM) system is designed to provide a useful diagnostic tool during both the commissioning and operational phases of the antiproton source. Simply stated the design goal is to provide single turn beam position information for intensities of >1x10**9 particles, and multi-turn (closed orbit) information for beam intensities of >1x10**7 particles, both with sub-millimeter resolution. It is anticipated that the system will be used during commissioning for establishing the first turn through the Debuncher and Accumulator, for aligning injection orbits, for providing information necessary to correct closed orbits, and for measuring various machine parameters (e.g. tunes, dispersion, aperture, chromaticity). During normal antiproton operation the system will be used to monitor the beam position througout the accumulation process.

There are 210 beam pickups in the system--120 in the Debuncher and 90 in the Accumulator. In general there is one pickup at each quadrupole (with horizontal pickups at F quadrupoles and vertical pickups at D quadrupoles). This results in more than five postion measurements per view per betatron wavelength in each ring, and provides more than sufficient information for precision alignment of closed, injection, and extraction orbits. The pickups themselves are either cut cylinders or rectangles, depending on location, with signals capacitively coupled from the beam. To maximize signal levels the pickups cover the full azimuth and every effort has gone into minimizing their capacitance to ground. The pickups are bidirectional to accomodate beams circulating in either direction and in the Accumulator also function as clearing electrodes.

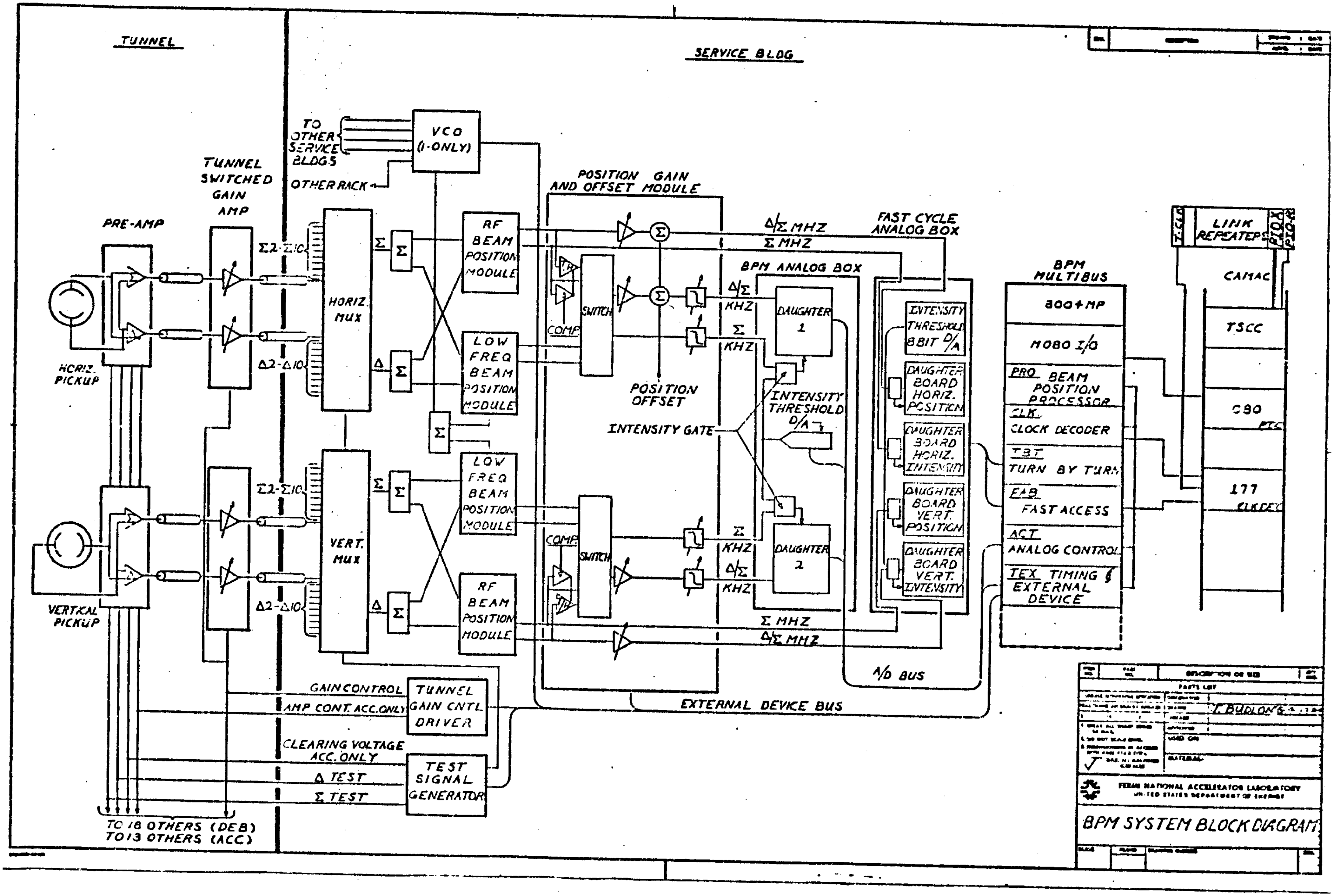
During the commissioning period ~1x10**10 protons will be injected into the Debuncher and Accumulator rings. In general these protons will be delivered from the Booster in 80 bunches at 52.8MHz, either directly (via the Booster-Debuncher line), or by way of the Main Ring to the Debuncher (forward injected via the Target-Debuncher line) or to the Accumulator (reverse injected through the Accumulator-Target line). The Booster-Debuncher line will also permit the use of circulating protons as a diagnostic tool after the commissioning period with minimal impact on any ongoing TeV II operations. For these modes of operation we have provided the capability of measuring orbits both over a single turn and averaged over multiple turns.

According to the latest TeV I design report ~7x10**7 antiprotons are injected into the Debuncher once every 2 seconds during the accumulation cycle. These antiprotons arrive in a train of 80 bunches with a spacing of 53.1MHz. In the Debuncher they are rotated one quarter of a turn in longitudinal phase space by a 53.1MHz RF system. Once rotated the beam is allowed to debunch. However, a low level wideband RF system is provided to preserve the 200nsec gap which is present at injection. After approximately 2 seconds in the Debuncher the beam is extracted and sent to the Accumulator. The 7x10**7 antiprotons are placed on an injection orbit with an average momentum 0.93% above the central orbit of the Accumulator. They are then quickly moved to the tail of the accumulated antiproton stack by a 6.3MHz RF system and subsequently cooled by the stochastic cooling systems. Eventually a core of up to 5x10**11 antiprotons is collected at an average momentum lying 0.69% below the central orbit value. Following accumulation ~1x10**11 antiprotons, in thirteen 52.8MHz bunches, are moved onto a momentum displaced extraction orbit and kicked out the extraction line in a single turn. The BPM system has been designed with the capability of observing the (single turn) injection orbit and circulating closed orbit in the Debuncher, and the (multi-turn) injection orbit, core orbit, and extraction orbit in the Accumulator.

A block diagram of the BPM system is given in Figure 1. Parallel systems are used for the signal processing of single turn and multiple turn measurements. Single/turn by turn measurements are processed by a high frequency (53MHz), wide bandwidth (5MHz) system which relies on 53MHz signals produced by the bunched beam. This system is very similar to the present Saver detection system. Multiple turn (closed orbit) measurements are processed through lower frequency (2.4MHz in the Debuncher and 6.3MHz in the Accumulator) , narrow bandwidth (100-1000Hz) systems which rely on naturally occurring gaps in the circulating beam, Schottky noise, and/or modulation produced by low frequency RF for signal generation. The bandwidth of these systems is chosen simply to cover the momentum spread in the beam. The narrow bandwidth produces an analog average which typically extends over several hundred turns and is necessary to reduce the contribution to position resolution from noise in the system. In addition to analog averaging we are prepared to average digitally up to 256 measurements at any particular pickup to obtain sub-millimeter resolution even at very low signal levels. Six systems of the type shown exist in each ring. Signals from the pickups are multiplexed so that each system services between 7 and 10 pickups.

Our desire to obtain good position resolution even at the low signal levels present during antiproton accumulation dictates the use of high impedence, low noise preamplifiers mounted directly on the pickups in the tunnel. We have chosen to produce sum and difference signals out of the preamps in order to minimize the requirements on gain balancing. The preamplifiers have a gain of 14/1db at 6/53MHz, a DC input impedence of 100K , noise of $2nV/\sqrt{Hz}$, and common mode rejection ranging from 55db at 6MHz to 48db at 53MHz. For reliable performance we have imposed the requirement that the magnitude of the sum signals transmitted on the cables running from the tunnel to the service building lie in the range 1-2000mV. Since the dynamic range of the signals allowed on the cables is small compared to the expected dynamic range of signals coming out of the preamps we also include in the tunnel gain switchable amplifiers capable of adding between 0-60db gain in 20db steps.

The digital signal processing is done through a multibus based system which is very similar to that used in the Saver. This allows a large amount of hardware and software to be directly copied from the Saver system. Provisions are made for testing and monitoring of the entire system.



TUNNEL
SERVICE BLDG
PRE-AMP
HORIZ. PICKUP
VERTICAL PICKUP
TUNNEL SWITCHED GAIN AMP
Σ2-Σ10
Δ2-Δ10
HORIZ. MUX
VERT. MUX
TO OTHER SERVICE BLDGS
OTHER RACK
VCO (I-ONLY)
RF BEAM POSITION MODULE
LOW FREQ BEAM POSITION MODULE
POSITION GAIN AND OFFSET MODULE
SWITCH
COMP
POSITION OFFSET
INTENSITY GATE
Δ/Σ MHZ
Σ MHZ
Δ/Σ KHZ
Σ KHZ
BPM ANALOG BOX
DAUGHTER 1
DAUGHTER 2
INTENSITY THRESHOLD D/A
FAST CYCLE ANALOG BOX
INTENSITY THRESHOLD 8BIT D/A
DAUGHTER BOARD HORIZ. POSITION
DAUGHTER BOARD HORIZ. INTENSITY
DAUGHTER BOARD VERT. POSITION
DAUGHTER BOARD VERT. INTENSITY
A/D BUS
EXTERNAL DEVICE BUS
BPM MULTIBUS
8004-MP
M080 I/O
PRO BEAM POSITION PROCESSOR
CLK CLOCK DECODER
TBT TURN BY TURN
FAB FAST ACCESS
ACT ANALOG CONTROL
TEX TIMING & EXTERNAL DEVICE
CAMAC
TSCC
C80
177
LINK REPEATERS
GAIN CONTROL
AMP CONT. ACC. ONLY
TUNNEL GAIN CNTL DRIVER
CLEARING VOLTAGE ACC. ONLY
Δ TEST
Σ TEST
TEST SIGNAL GENERATOR
TO 18 OTHERS (DEB)
TO 13 OTHERS (ACC)
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
BPM SYSTEM BLOCK DIAGRAM

II. PICKUP DESIGN AND SENSITIVITY

The pickups used in the Tev I BPM system come in the three varieties shown in Figure 2. As we shall see later it is important to minimize both the capacitance/length of the pickups and the coupling capacitance between the two plates. We have done this by keeping the outer conductor >2cm away from the pickup plates and by leaving a 6mm gap between the two plates. The circular pickups shown in the figure are used in the Debuncher and in the low dispersion regions of the Accumulator. The rectangular pickup is used in the high dispersion regions of the Accumulator. It can be shown that with the given geometry both styles of pickups have a response which is exactly linear in the beam position. (See e.g. $\bar{p}$ Note 332.)

To calculate the response of the pickups we use a model which is displayed in Figure 3. The model is valid in the regime $\omega >> 2c/L$ i.e. for pickups whose length is small compared to the wavelength corresponding to the operating frequency. The quantities given in the figure are defined as:

C_0 =Capacitance of entire pickup to ground.

R =Resistance to ground of each electrode.

$I_\pm$=Induced current on each pickup.
$=\alpha_\pm \theta m I$
where $\alpha_+ = 1/2(1+x/a)$
$\alpha_- = 1/2(1-x/a)$
θ =length of pickup/mean radius of ring
$m=(\omega/\omega_0)$=harmonic of the revolution frequency
I=Fourier component of the beam current at frequency .
a=apparent aperture of the pickup

C_T=Coupling capacitance between plates.

The sum (V1+V2) and difference (V1-V2) voltages are then given by,

$$V_\Sigma = \frac{Rm\theta}{1+\frac{i\omega RC_0}{2}} I \quad , \quad V_\Delta = \frac{Rm\theta}{1+\frac{i\omega R(C_0+4C_T)}{2}} I \left(\frac{x}{a}\right)$$

We see that the sum signal is independent of both the position of the beam and the coupling capacitance. The difference signal is linear in the position with a magnitude which depends on the coupling between the plates. The beam position is derived from the sum and difference signals by,

$$\left(\frac{x}{r}\right) = \beta \frac{V_\Delta}{V_\Sigma}$$

where

$$\beta = \frac{a}{r} = \left(1 + \frac{4C_T}{C_0}\right) \left(\frac{L}{L-2\ell}\right)$$

and 2r is the (physical) full width of the pickup.

A prototype pickup has been built and measured. It is found to have,

C_o=75pf
C_T=11pf
L = 4"
l =.375"

These values give a predicted β of 1.95. The prototype has been measured using a wire driven with a known current at a known frequency. The absolute signal level, linearity, and sensitivity β are all exactly as expected.

To calculate the actual signal levels coming out of the pickups during operation with circulating beams we need to know something about the frequency spectrum of the circulating beams. We will look at four different types of beam structures which need to be seen by our system:

1. Bunched Beam. $I(\omega)=\sqrt{2}\, Nef_o$

2. Beam with gap. $I(\omega)=\sqrt{2}\, Nef_o \sin(mF\pi)/Fm\pi$
   where
   m=harmonic number, ω/ω_o
   F=fraction of the ring full

3. Bunched locally. $I(\omega)=\frac{\sqrt{2}\, Nef_o}{2n+1}\left(1+\frac{2\cos\ (\pi m(n+1)/h)\sin(\pi mn/h)}{\sin\ (\pi m/h)}\right.$
   where
   2n +1=number of bunches
   m =harmonic number, = ω/ω_o
   h =harmonic number of the bunch frequency =ω_{rf}/ω_o

4. Coasting beam. $I(\omega)=\sqrt{2N}\, ef_o$

In all expressions $I(\omega)$ is the rms component of the beam current at the frequency ω, N is the number of particles in the ring, e is the charge of the electron, and f_c is the revolution frequency of the ring. We have ignored in 1.-3. and will continue to ignore form factors arising from finite bunch lengths.

We note from the expressions given above for the sum and difference signals that as a function of the terminating resistance, R, signal levels are maximized with $\omega RC_o \gg 1$. This is the regime we have chosen to work in. The ultimate measurement precision of the BPM system depends upon the noise associated with the sum and difference signals. If we let V_N be the rms noise on the sum signal (assumed to be the same on the difference signal) then the rms deviation of the measured position x is given by,

$$\sigma_x = \frac{\beta r V_N}{V_\Sigma}$$

The position resolution is directly proportional to the sensitivity, the width of the pickup, and the signal to noise. For a sensitivity of β=2 and a width of 2r=270mm (worst case), 1mm resolution requires a signal to noise ratio of 270/1. The measurement accuracy depends on three factors: the accuracy with which the pickups are located within the quadrupoles, the degree to which the capacitances of the two pickup plates are equal, and the common mode rejection of the difference amplifier. For 1mm accuracy the capacitances have to be matched to about 1%, the CMRR has to be at least 48db, and of course the center of the pickup must correspond to the center of the quadrupole to less than a millimeter.

There are two primary sources of noise in the BPM system. They are thermal noise generated in the terminating resistance on the plates, and amplifier noise generated in the preamplifier. We assume that the gain of the preamplifier is sufficient that contributions to the noise from elements downstream are negligible. The contribution from resistor noise is given by,

$$V_N^2 = \frac{4kT\ \Delta f R}{1+(\omega R C_o/2)^2}$$

where kT=4x10**-21, and Δf is the bandwidth. For our mode of operation this noise source is completely negligible compared to amplifier noise. The noise level of the preamplifier we have designed has been measured to be,

$$V_N = 2\times10^{-9}\ \text{Volts}\ \ \sqrt{\Delta f\,(\text{Hz})}$$

This is close to what is predicted for FET based amplifiers (see $\bar{\text{p}}$ note 341). We can now look at how the signal to noise depends on the capacitance, C_o, the length of the pickup, θ, the harmonic number of the detection frequency, m, and the bandwidth, Δf in the limit $\omega RC >> 1$. Using our expressions for V_Σ and for the harmonic content of the circualting beam we find for cases 1-4,

1. $V_\Sigma = \sqrt{2}\ Ne\theta/\pi C_o$
2. $V_\Sigma = \sqrt{2}\ Ne\theta \sin(m\pi F)/\pi^2 C_o mF$
3. $V_\Sigma = \dfrac{\sqrt{2}\ Ne\theta}{\pi C_o(2n+1)}\left(1 + \dfrac{2\cos\ (\pi m(n+1)/h)\ \sin(\pi mn/h)}{\sin\ (\pi m/h)}\right)$
4. $V_\Sigma = \sqrt{2N}\ e\theta/\pi C_o$

Since in our case the noise is directly proportional to the $\sqrt{\text{bandwidth}}$ expressions for signal to noise are obtained simply by appending a $\sqrt{\Delta f}$ to the denominators of the above. In all cases the signal to noise ratio is inversely proportional to the capacitance per unit length of the pickup times the $\sqrt{\text{bandwidth}}$. This is why we have made every effort to reduce the capacitance/length and have designed a narrow bandwidth system. The bandwidths are chosen (for multiple turn measurements) simply to cover the frequency spread within the beam,

$$\Delta f = \eta \Delta p/p$$

where η is the momentum compaction factor. (η=.006 in the Debuncher and .022 in the Accumulator) and $\Delta p/p$ the momentum spread.

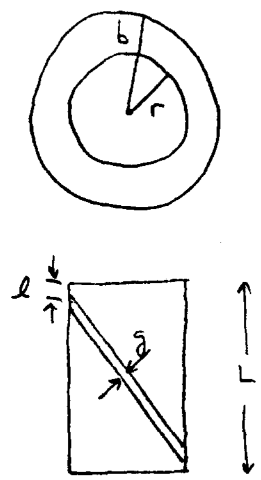
We have chosen a dual system for signal processing. A high frequency (53MHz) system is used for measurements of the bunched beams which will be used during commissioning--type 1 above. Lower frequency systems are used for types 2-4. In the Debuncher we use an m=4 (2.4MHz) system for measuring a beam which is anticipated to have F=80/90. In the Accumulator we use m=10 (6.3MHz) for a beam which during injection will have F=80/84. For the case of observing the extraction orbit in the Accumulator (type 3) either the 53MHz or 6.3MHz system can be used. Schottky signals for measurement of the Accumulator core (type 4) are also observed at 6.3MHz.

In Table 1 we summarize the expected signal levels and position resolution for the conditions under which the BPM system will operate. We have assumed a total capacitance somewhat higher than what has been measured on the prototype in order to anticipate any stray capacitance which may arise from connectors or the preamp. In the Accumulator we have also quoted worst case resolutions corresponding to the high dispersion pickups. Resolution in the low dispersion pickups should be almost a factor of three better. The table indicates that submillimeter resolution is indeed expected on all measurements provided that we are willing to average digitally up to one hundred measurements during certain phases of antiproton operation. Digital averaging will be discussed in more detail in Section V.

We conclude this sections with a series of figures (Fig 4-8) showing the position resolution as a function of the number of circulating particles under the various operating conditions. Curves are included for single turn, multiple turn, and multiple turn with digital averaging.

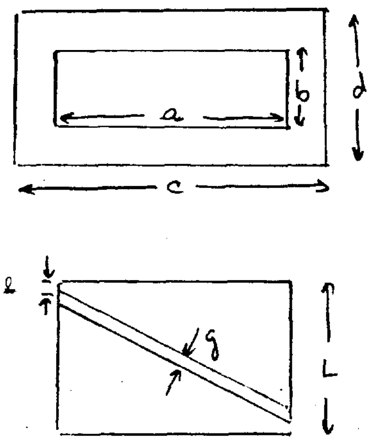
BPM Physical Dimensions

Circular



	Debuncher	Accumulator	
r =	7.1	5.0	cm
b =	8.9	6.4	cm
L =	10	10	cm
l =	0.9	0.9	cm
g =	0.6	0.6	cm

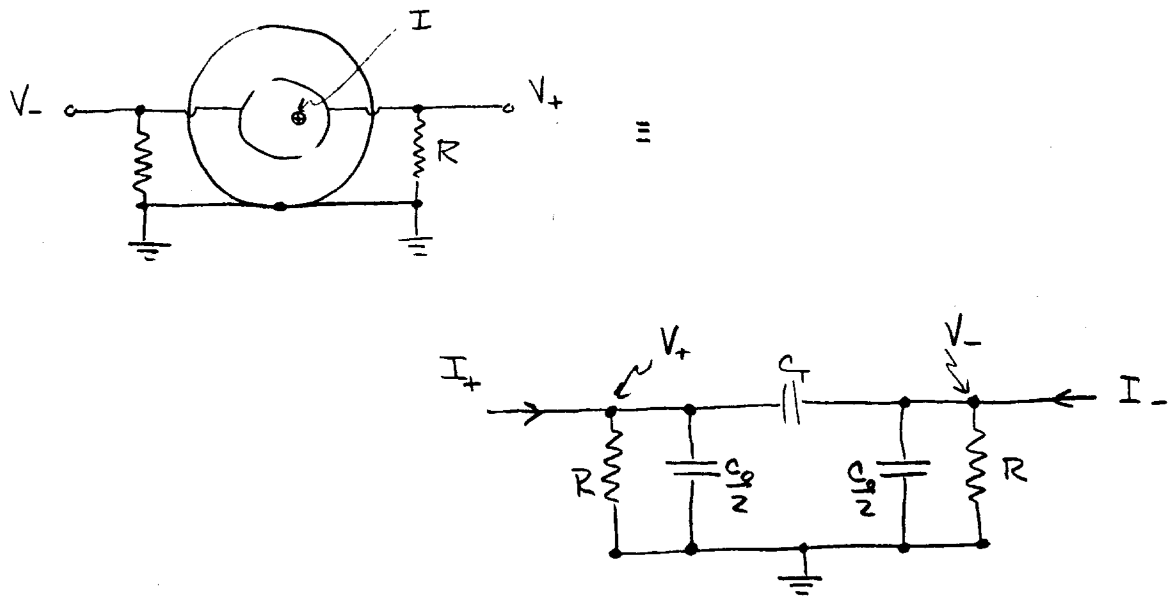
Rectangular



a =	27cm
b =	4.9cm
c =	31 cm
d =	10 cm
L =	10cm
l =	0.9cm
g =	0.6cm

Figure 2

Pickup Response



where $I_{+,-} = \alpha_{+,-}\, m \theta I$

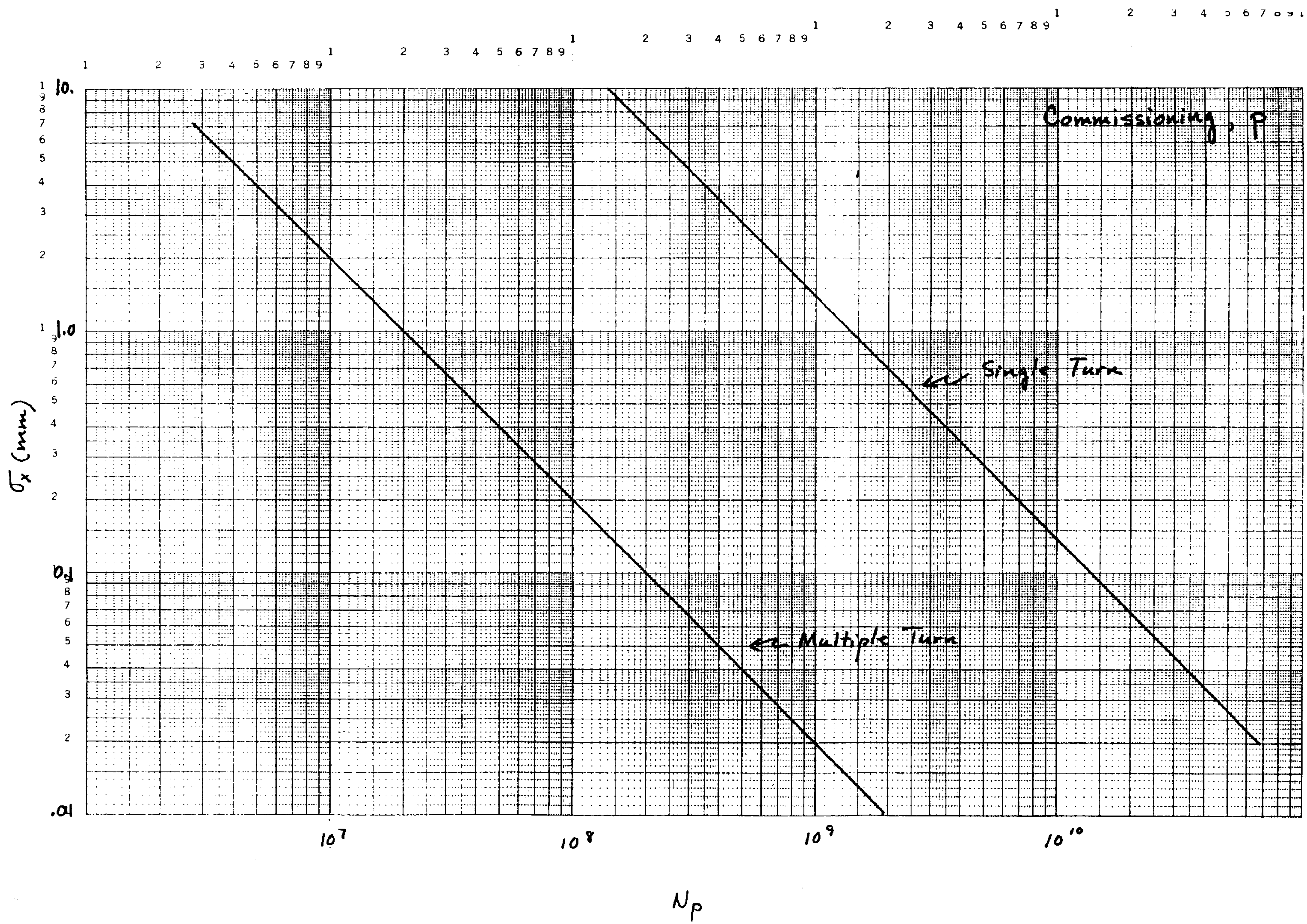
Figure 3

TABLE 1. BPM RESPONSE FOR $\omega RC >> 1$, $\theta=1.2\times10^{-3}$, $C_o=100$ pf, $\beta=2$, $V_N=2nV/\sqrt{Hz}$

CONDITION	N	f (MHz)	Δf (Hz)	V_Σ (uV)	V_N (uV)	σ_x (mm)
1. Commissioning, p: TBT	1×10^{10}	53	5.3 M	8600	4.6	0.14
: MT	"	"	1100	"	.066	0.002
2. Debuncher, $\bar{p}$, F=80/90	7×10^{7}	2.4	500	5.3	.045	1.2
3. Debuncher, π^-(Inj.): ST	3.5×10^{9}	53	5.3M	3000	4.6	0.2
4. Acc. Inject, $\bar{p}$, F=80/84	7×10^{7}	6.3	1000	2.0	.063	8.5
5. Acc. Inject, $\bar{p}$, Bunched*	7×10^{7}	6.3	500	60.2	.045	0.2
6. Acc. Core, $\bar{p}$, Schottky	5×10^{11}	6.3	70	0.6	.017	7.7
7. Acc. Core, $\bar{p}$, 10^{-3} Mod.*	5×10^{11}	6.3	500	430	.045	0.03
8. Extraction Pre-Pulse, $\bar{p}$	1×10^{9}	53	1200	860	.069	0.02
	"	6.3	150	180	.025	0.04
:LT	"	53	5.3M	5300	4.6	0.2
9. Extraction, $\bar{p}$	1×10^{11}	53	5.3M		x 100	

TBT=turn by turn, MT=multiturn, ST=single turn, LT=last turn

*During injection into the Accumulator a modulation of approx. 10^{-3} will be induced on the core by the 6.3 MHz RF. This will most likely result in conditions 5&7 obscuring each other.



Commissioning, P
Single Turn
Multiple Turn
10.
1.0
0.1
.01
σ_x (mm)
10^7
10^8
10^9
10^{10}
N_p

Figure 4

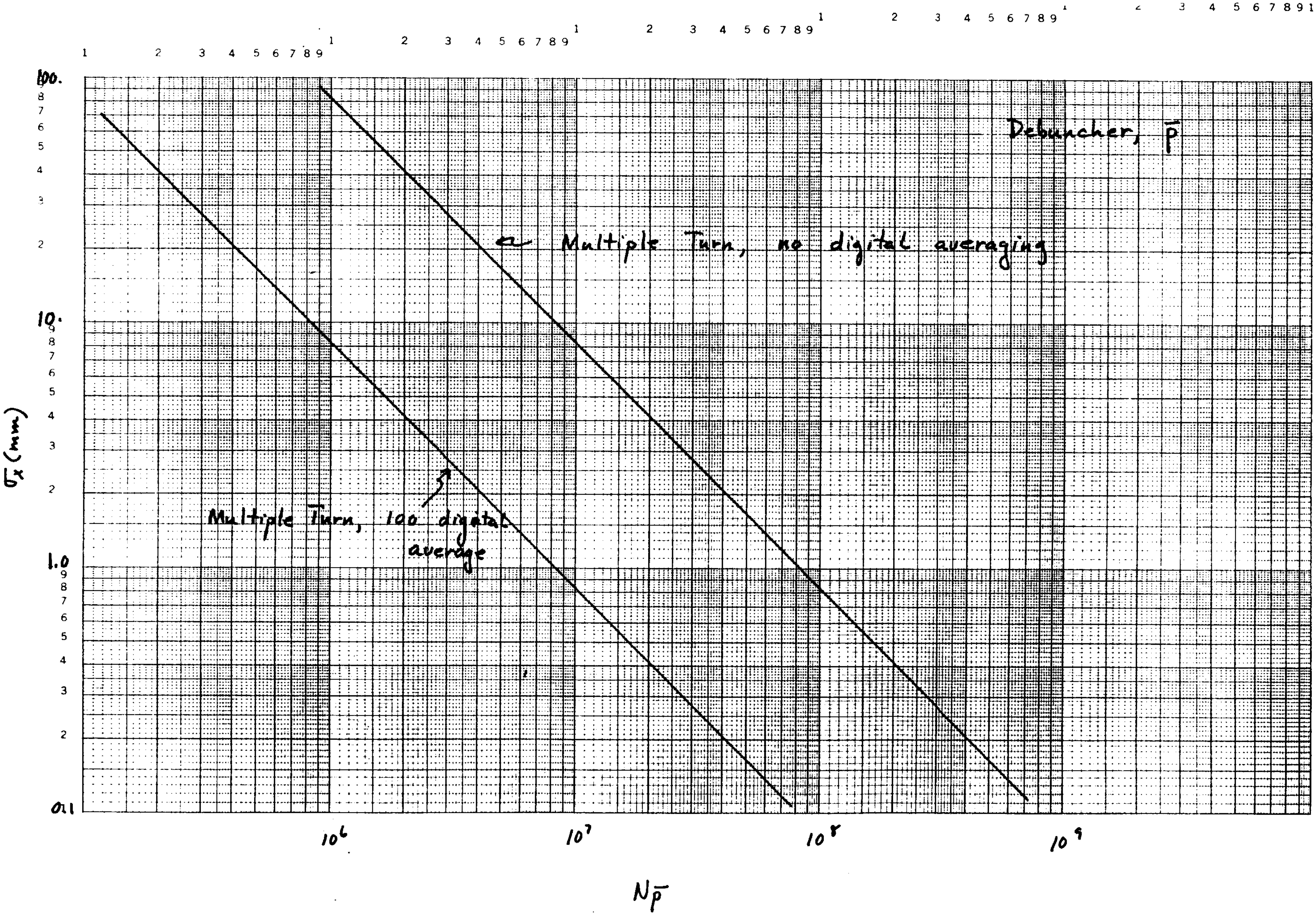

Debuncher, $\bar{p}$
Multiple Turn, no digital averaging
Multiple Turn, 100 digital average
σ_x (mm)
100.
10.
1.0
0.1
10^6
10^7
10^8
10^9
$N_{\bar{p}}$

Figure 5

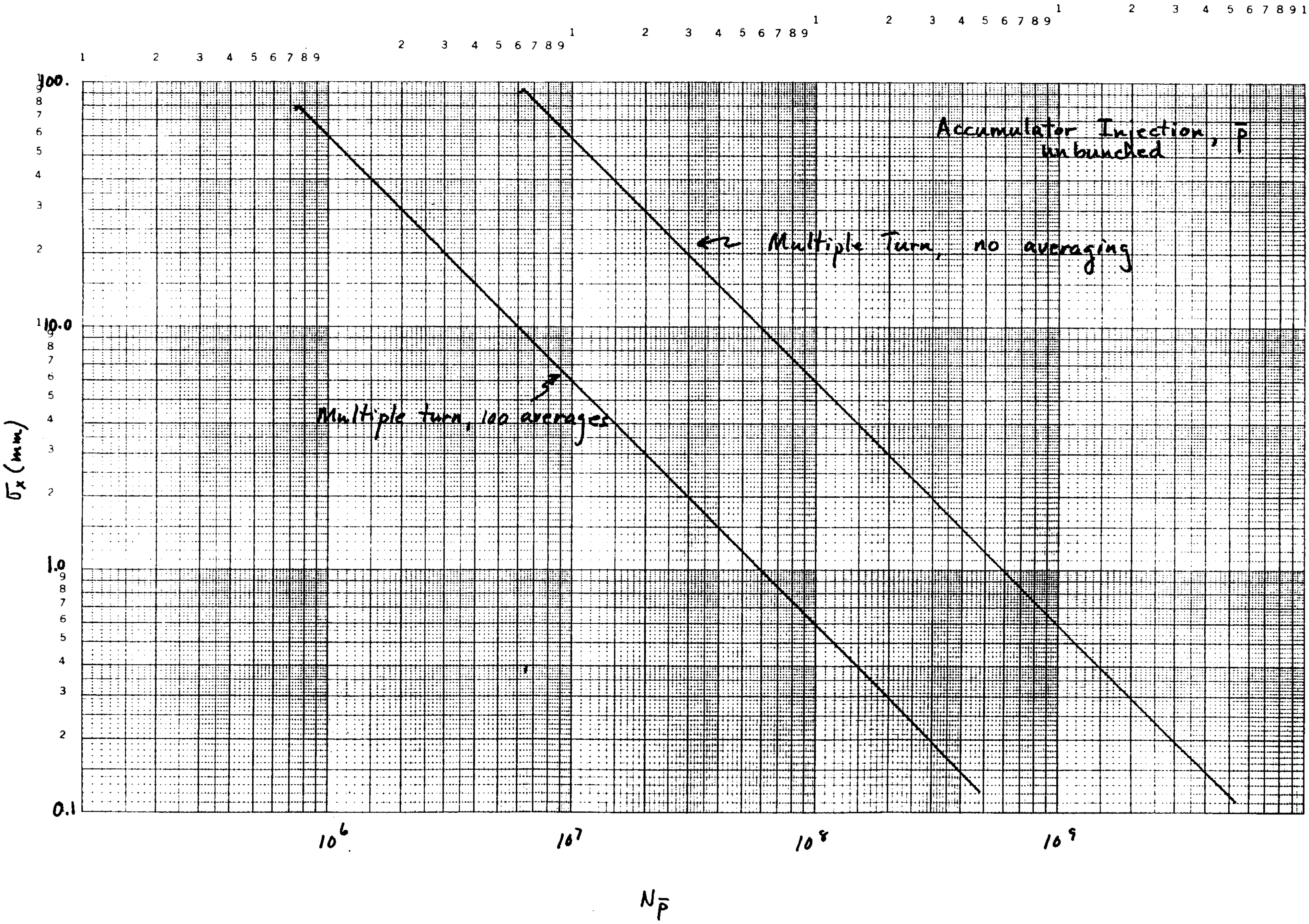
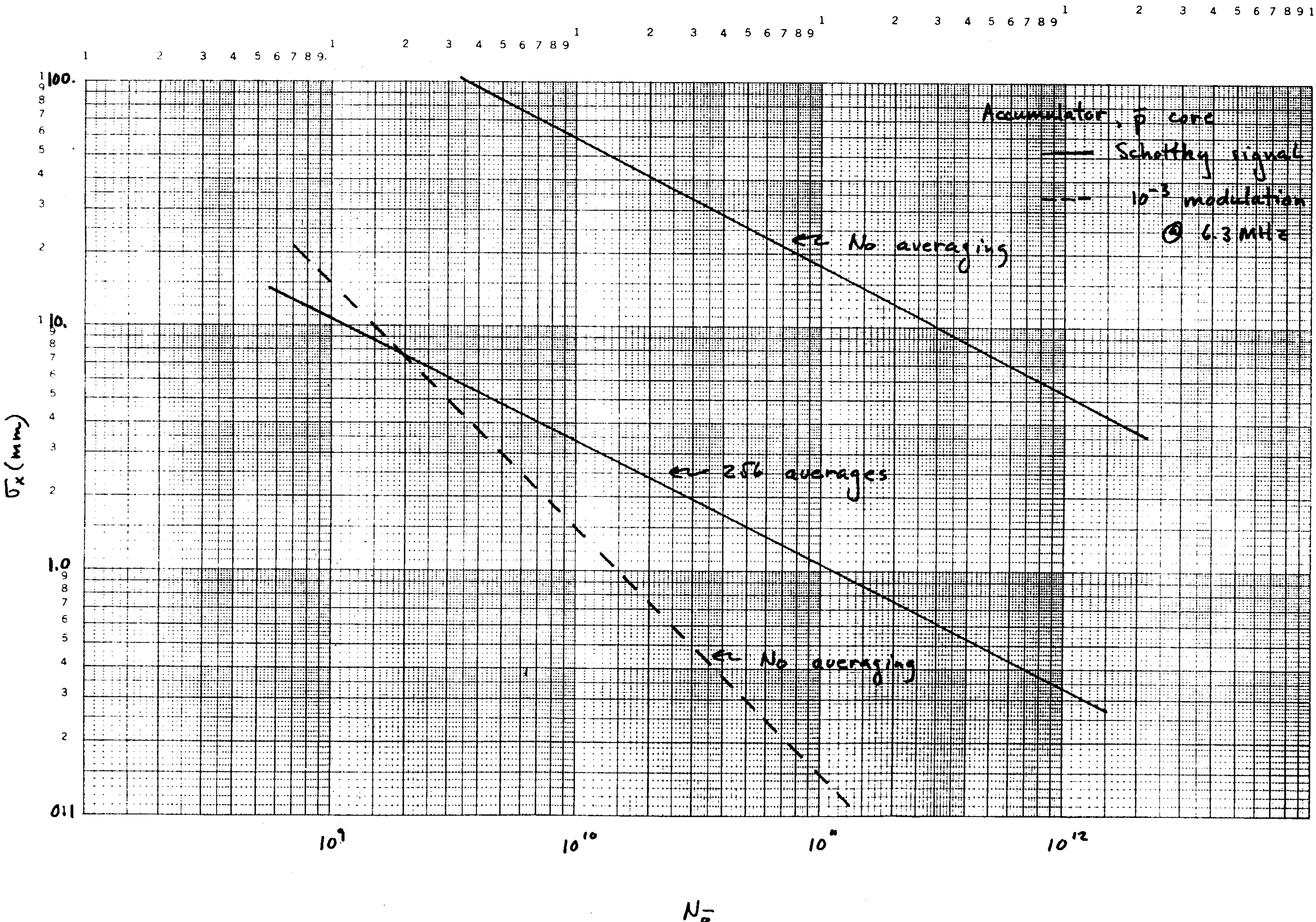
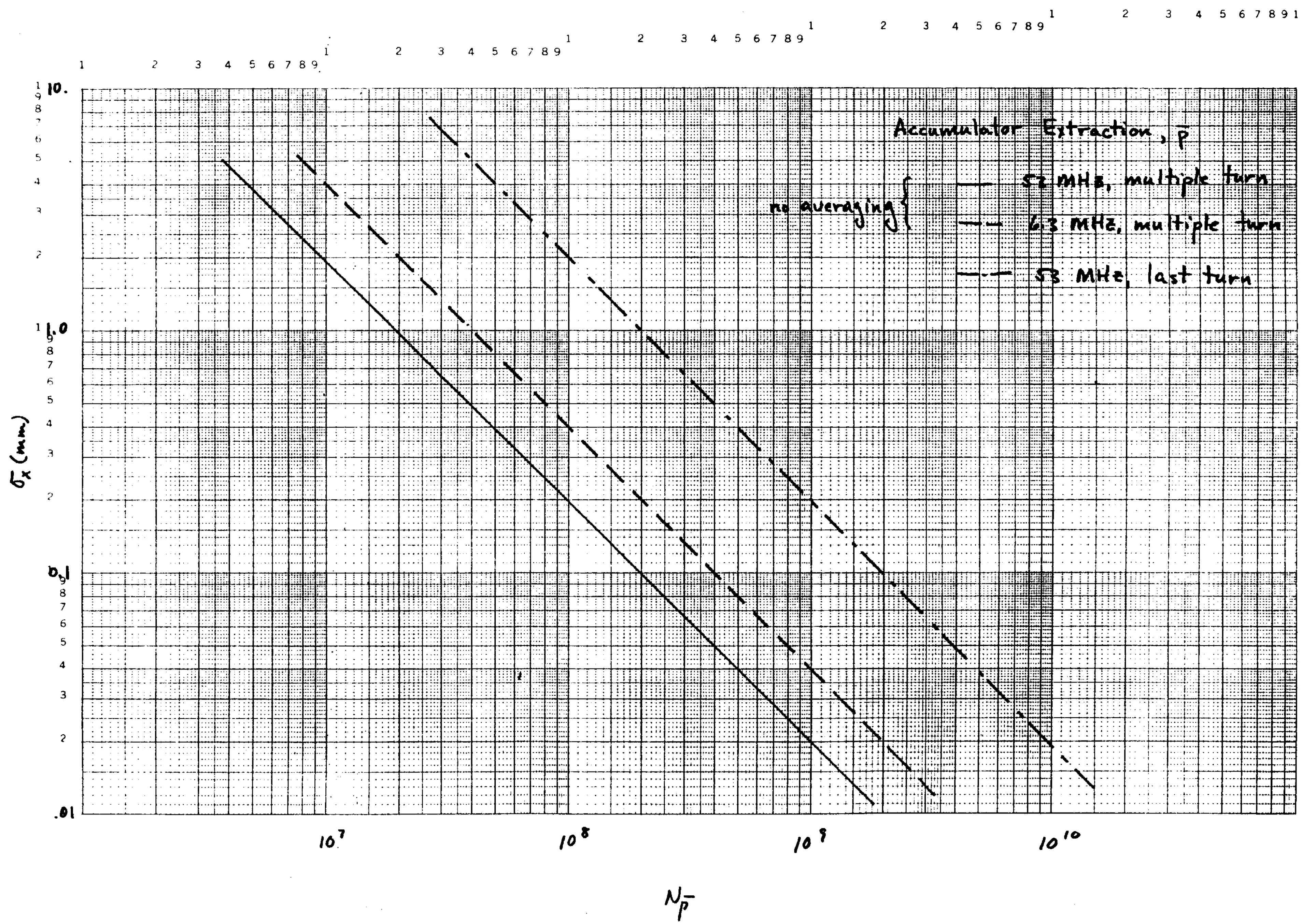

Accumulator Injection, $\bar{p}$ unbunched
Multiple Turn, no averaging
Multiple turn, 100 averages
σ_x (mm)
100.
10.0
1.0
0.1
10^6
10^7
10^8
10^9
$N_{\bar{p}}$

Figure 6



Accumulator, $\bar{p}$ core
Schottky signal
10^{-3} modulation
@ 6.3 MHz
No averaging
256 averages
No averaging
100.
10.
1.0
σ_x (mm)
10^9
10^{10}
10^{11}
10^{12}
$N_{\bar{p}}$

Figure 7



Accumulator Extraction, $\bar{p}$
no averaging
52 MHz, multiple turn
6.3 MHz, multiple turn
53 MHz, last turn
σ_x (mm)
10.
1.0
0.1
.01
10^7
10^8
10^9
10^{10}
$N_{\bar{p}}$

Figure 8

III. TUNNEL PREAMPS AND SWITCHABLE GAIN AMPLIFIERS

Design Philosophy

The desire to measure low intensity and weakly modulated beams results in the need to be sensitive to small signal levels. Under some conditions the signals are less than one microvolt into a high impedance load. To preserve signal integrity against external noise and possible attenuation due to unwanted capacitance, preamplifiers will be connected directly to the feedthroughs on the pick-ups. The preamp will be a combination sum and difference amplifier with FET inputs. Taking the sum and difference of the two electrode signals at the front end minimizes any apparent center position offset that could otherwise be introduced by unbalanced gain in downstream amplifiers. In order to further compete with noise picked up on signal cables between the tunnel and the service building electronics, additional amplification in the tunnel is necessary. A design goal is to maintain a minimum sum signal of one millivolt rms on the cables to the service buildings. The maximum peak signal allowed on the cables is 2 volts,limited by the solid state multiplexers used in the upstairs processing electronics. The large dynamic range of signals requires the gain of this additional amplification to be remotely selectable. Figure 9 shows the expected signal voltages available at the pick-up electrodes for the various beam conditions. Figure 10 shows the corresponding sum signal voltages, after amplification and preamp gain switching, available for processing in the service buildings. Figure 11 is a key to Figures 9 and 10.

Circuit Requirements

Random noise added to the signals by the amplifiers determines the ultimate beam position resolution. The design goal for preamp noise is 2 nanovolts per root hertz to give satisfactory position resolution. The input impedance of the preamp is to be kept as high as possible consistent with all other requirements.

To measure beam position for the varied modes of operation and wide range of intensities, the amplifiers need to be able to process signals as low as 0.25 microvolts rms and as high as 6 volts peak. The maximum total tunnel gain must be the order of 75db to boost the smallest signals to the one millivolt level. The minimum tunnel gain must be about -20db to limit the maximum peak signals to the a level acceptable to the solid state multiplexers. The tunnel gain must be selectable in approximately 20db steps.

Position measurement accuracy is limited by the common mode rejection of the preamp difference amplifier. In the largest pick-up, a difference signal equal to 0.3% of the sum signal corresponds to a 1mm positon displacement. This is equivalent to a common mode rejection ratio of 48db. Unbalanced gain tracking throughout the sum and difference channels leads to position sensitivity errors and equivalent position errors at off-center positions. Tracking to 1% is required to maintain accuracy to 1 mm at the edge of the largest pick-up. The planned signal processing scheme requires phase tracking between the sum and difference signals at the level of about 5 degrees. The preamps must also provide a means to apply a dc clearing voltage of approximately 100 volts to the pick-up electrodes.

Preamp Circuit Design and Performance

Figure 12 is a schematic diagram of the present stage of design of the preamplifier. Table 2 lists the circuit's measured performance. The sum and difference amplifiers connect in parallel to each electrode of a pick-up. Amplifier inputs from the electrodes are coupled through a blocking capacitor to allow the dc clearing voltage to be applied to the electrodes. This voltage can be applied through a BNC connector on the preamp module. Up to 150 volts is acceptable.

This amplifier design uses Siliconix 2N5911 matched dual channel JFETs. This component, in addition to low noise, also has the advantage of two matched devices in a single package to enhance and stabilize common mode rejection of the differential stages.

The difference amplifier consists of two standard differential stages with bipolar transistor current sources. The secondstage is followed by a bipolar emitter follower output transistor. The sum amplifier consists of two FETs with a common drain resistor followed by a second FET stage. Again there is a bipolar emitter follower output. Each preamp will have local voltage regulators allowing a number of preamps (about one sixth of each ring) to be powered in parallel by supplies located in the service buildings. The power requirement of each preamp is plus and minus 18 to 24 volts at 100 milliamps.

The proposed signal processor requires a 15db signal to noise ratio in a 1KHz bandwidth. This determines the low end of the useful dynamic range of this preamp. With 2 nanovolts per root hertz input noise, the corresponding 1KHz noise is 63 nanovolts. Therefore, the lowest useful input signal is approximately 0.35 microvolts. The high end of the amplifier range is limited by compression in the emitter follower output. This occurs with 0.25 volt peak inputs for signals with the spectrum expected. This range is adequate for signals encountered in the Debuncher. The Accumulator, however, requires a larger range at the high end. To accomodate this without overloading either the output stage or the FET front end, units used in the Accumulator will have parallel preamps in one housing, one of which will have a 50:1 capacitive divider at its input. There will be a solid state switch at the preamp output to select between the two amplifiers. The state of the DPDT PIN diode switch is selected by a signal of either plus 5 to 7 volts or minus 5 to 7 volts at 50 milliamps. The switch control lines for one sixth of the ring will be connected in parallel for common control. Control is provided through an interface chassis by the BPM microprocessor external device bus.

As shown in Table 2, the achieved common mode rejection of the amplifier is satisfactory. Trimmer capacitors are included in the circuit on the signal inputs to balance input impedances and differences between electrode capacitances. A test signal input, common to both signal inputs, is provided to facilitate balancing when the preamp is connected to a beam pick-up. Another test input connected only to one input is provided to allow monitoring of the gain and tracking of the sum and difference channels.

The nominal voltage gain of the preamps is 14db below 10Mhz, rolling off to about 2db at 53Mhz. In terms of noise and absolute signal strength the rolloff is not a problem since operation at this frequency is not necessary under very low signal conditions. It does, however, require matching the rolloff between the sum and difference channels to maintain gain and phase tracking. The rolloff in this design is a consequence of the parallel combination of the FET drain resistors and the capacitance at that point.

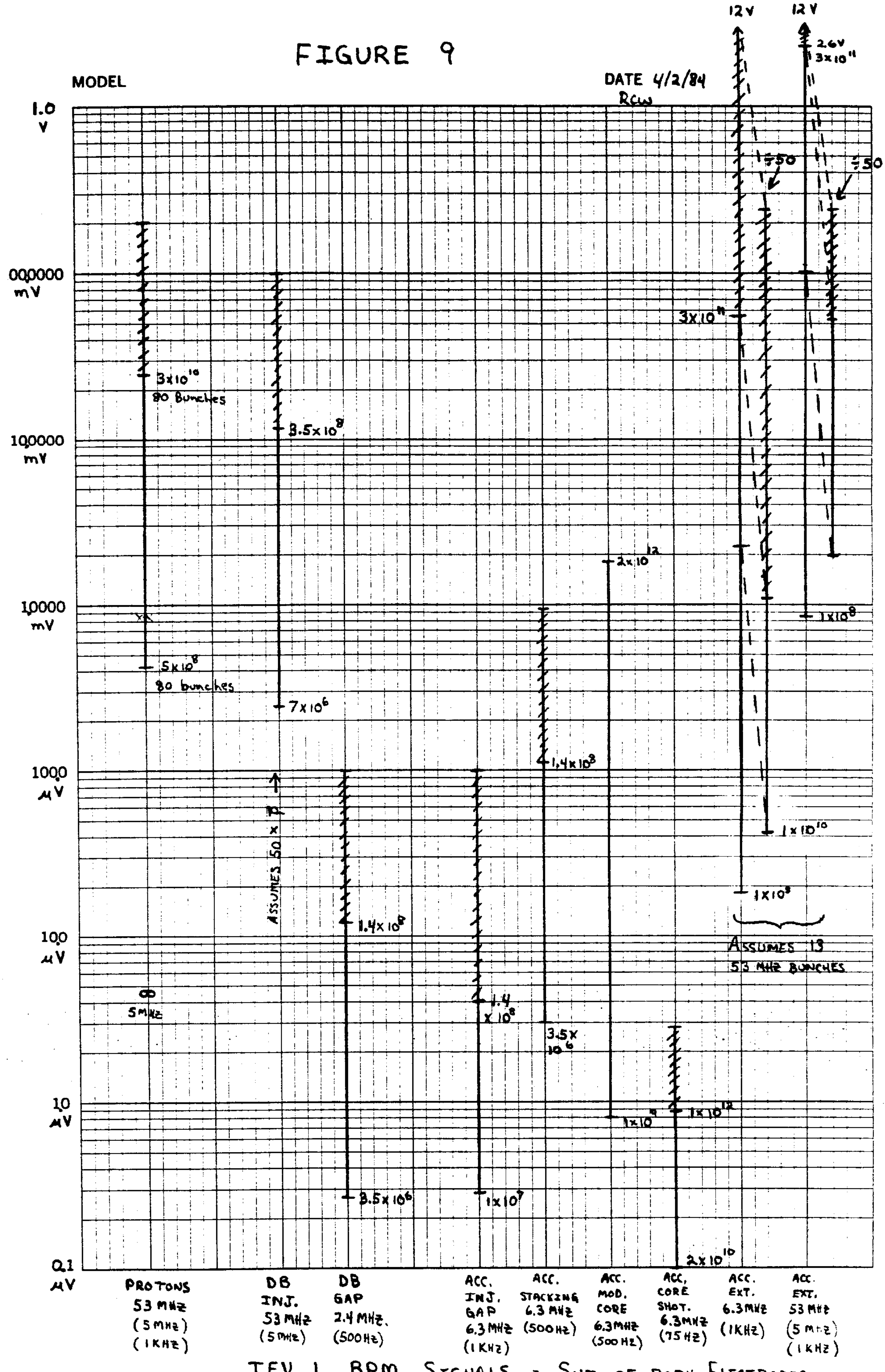
Input protection circuitry is provided to limit peak voltages appearing at the FET gates to approximately 8 volts.

Tunnel Switchable Gain Amplifiers

A matched pair of switchable gain amplifiers located in the tunnel near each preamp provide the necessary additional gain to the sum and difference signals. Signal paths between the preamps and these amplifiers need to be kept as short and as well shielded as possible. Figure 13 shows a functional block diagram of the required amplifier. Table 3 lists the necessary specifications.

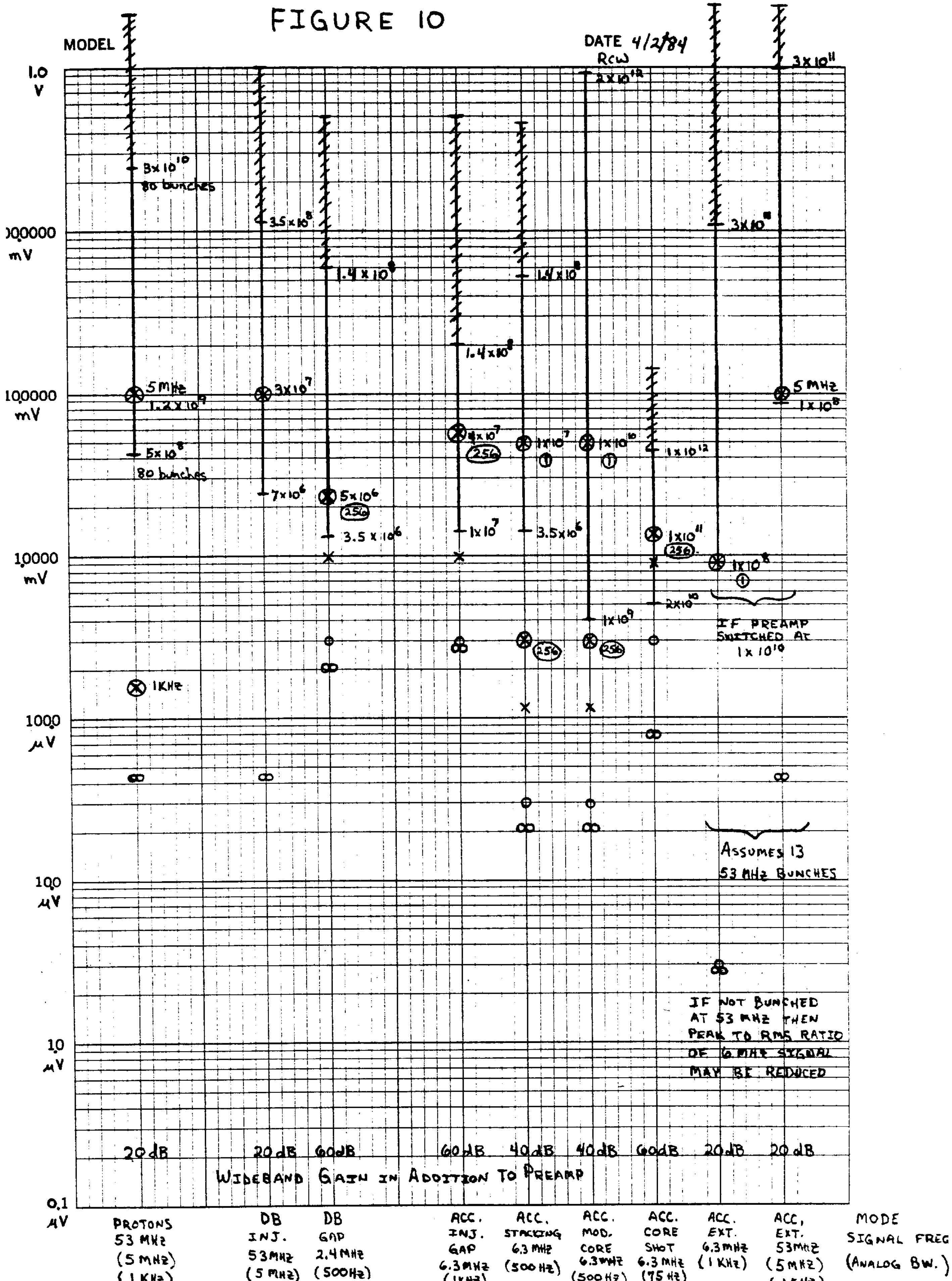
A 50 ohm system noise figure of 10db or less is sufficient to make the noise contribution of these amplifiers negligible. The gain and phase matching of the amplifiers in the sum and difference channels have the same effect on the measurement results as discussed above in the preamp section. Output power of each stage needs to be sufficient to supply up to 1.5 volts peak without compression. The amplifier units need to provide a 75 to 100 ohm dc path to ground at their output. This is required by the solid state multiplexers. The amplifiers will drive the signals over 50 ohm 3/8 inch semi-rigid coaxial cables to the multiplexers in the service buildings. The amplifiers, like the preamps will be powered in parallel by supplies located in the service buildings. The control signals, also paralleled, will come from an interface chassis connected to the BPM microprocessor external device bus. Operationally, the gain selection is determined by the desired measurement mode. The dynamic range of downstream electronics is, adequate to cover the expected range of beam intensities in a given mode.

FIGURE 9



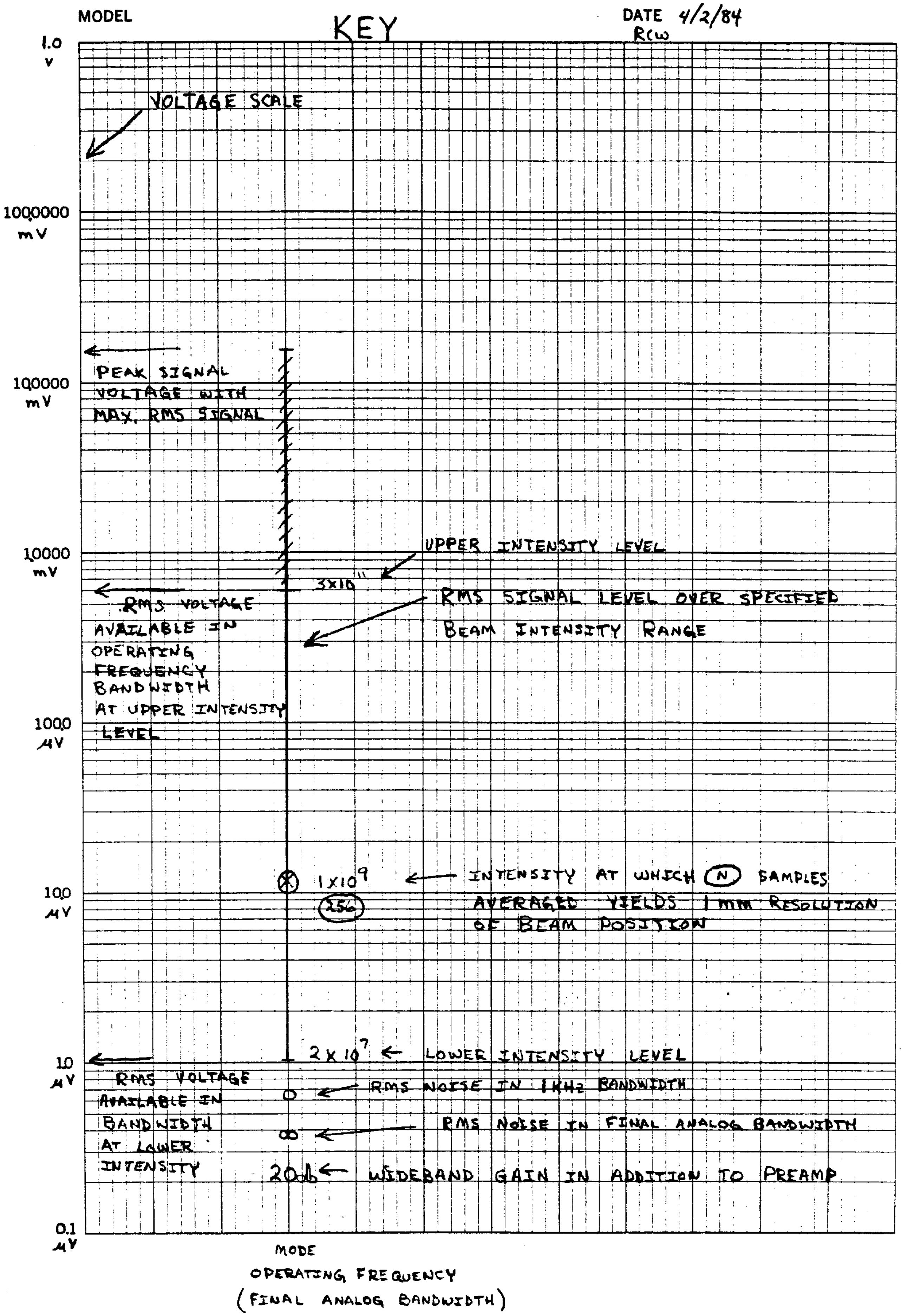
TEV I BPM SIGNALS - SUM OF BOTH ELECTRODES

FIGURE 10



TEV I BPM - SUM SIGNALS ON CABLES

FIGURE 11


MODEL
KEY
DATE 4/2/84
RCW
1.0 V
VOLTAGE SCALE
1000.0000 mV
PEAK SIGNAL VOLTAGE WITH MAX. RMS SIGNAL
100.0000 mV
10.000 mV
UPPER INTENSITY LEVEL
3x10^11
RMS VOLTAGE AVAILABLE IN OPERATING FREQUENCY BANDWIDTH AT UPPER INTENSITY LEVEL
RMS SIGNAL LEVEL OVER SPECIFIED BEAM INTENSITY RANGE
1000 µV
1x10^9
256
INTENSITY AT WHICH (N) SAMPLES AVERAGED YIELDS 1 mm RESOLUTION OF BEAM POSITION
100 µV
2x10^7
LOWER INTENSITY LEVEL
10 µV
RMS VOLTAGE AVAILABLE IN BANDWIDTH AT LOWER INTENSITY
RMS NOISE IN 1KHz BANDWIDTH
RMS NOISE IN FINAL ANALOG BANDWIDTH
20db
WIDEBAND GAIN IN ADDITION TO PREAMP
0.1 µV
MODE
OPERATING FREQUENCY
(FINAL ANALOG BANDWIDTH)

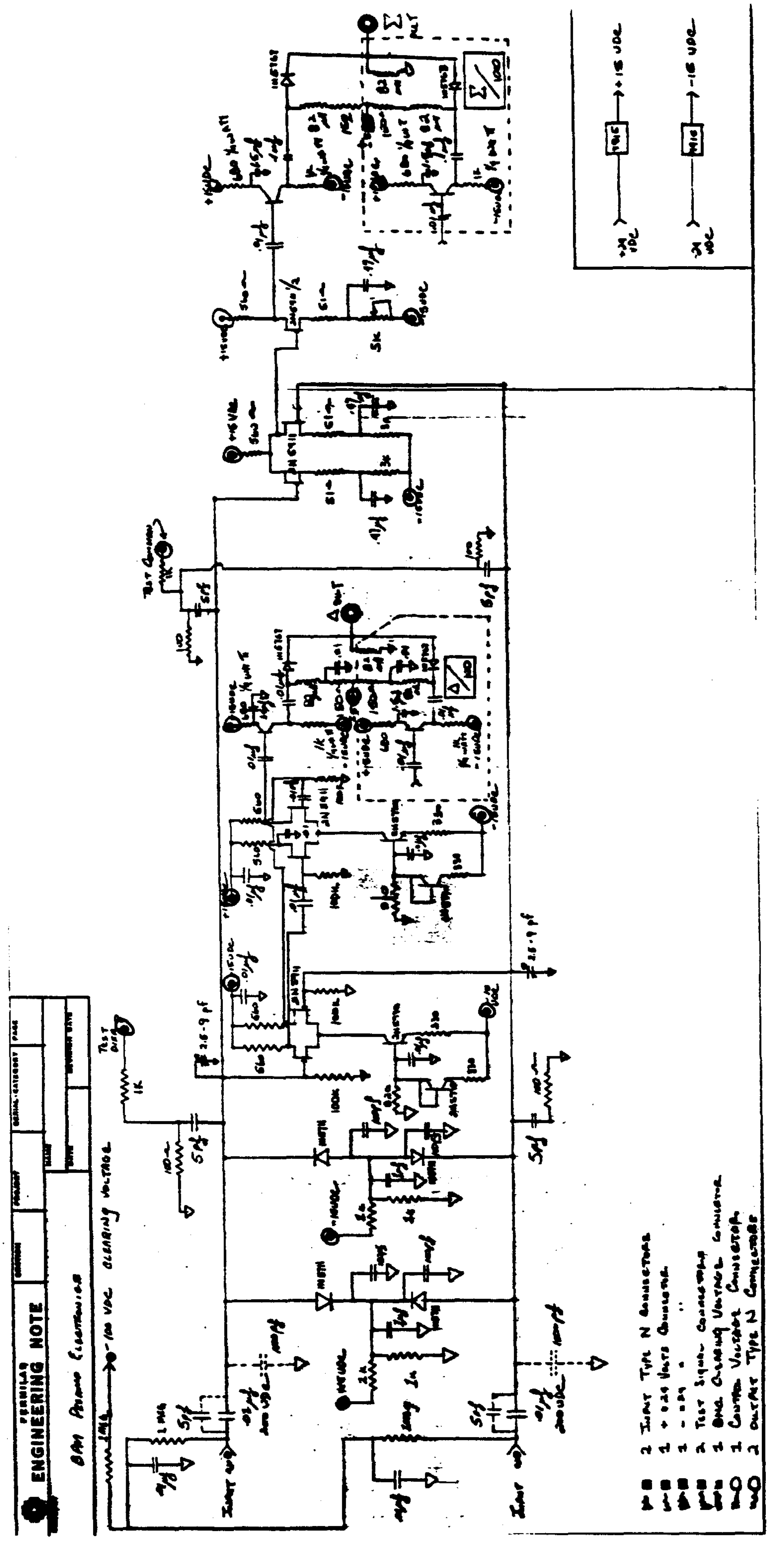


FIGURE 12

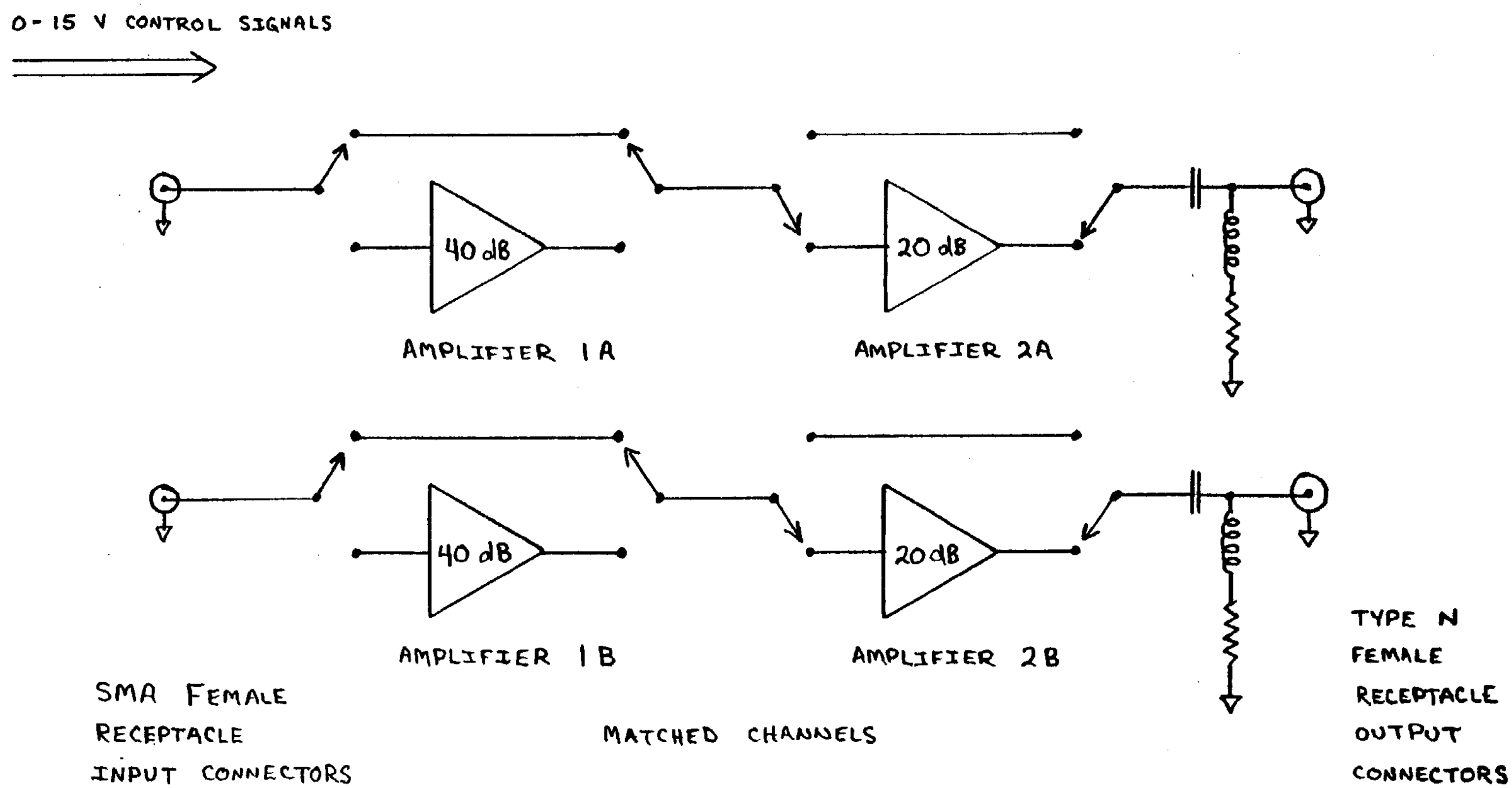
TABLE 2

TEV 1 PREAMPLIFIER PERFORMANCE

Frequency	2.3 MHZ	6.3 MHZ	53 MHZ
Input Impedance	35pf in parallel with 100K ohms		
Sum Amp Voltage Gain	14db	14db	2db
Difference Amp Voltage Gain	14db	14db	2db
Sum and Diff. Gain Tracking	< 0.2db	< 0.2db	< 0.5db
Sum and Diff. Phase Tracking	< 1 deg.	< 1 deg.	< 2 deg.
Difference Amp CMRR	> 55db	> 55db	> 48db
Equivalent Input Noise Voltage (per root hertz)	2nv	2nv	10nv
Dynamic Range (15db S/N in 1KHZ) (Without 34db Extension)	100db	100db	100db

Switchable Gain Amplifier

Functional Diagram



Both Channels will be set to same gain at any given time

FIGURE 13

TABLE 3

TEV 1 SWITCHABLE GAIN AMPLIFIER SPECIFICATIONS

General Specs for Each Channel

Nominal Input/Output Impedance:
50 ohms

Nominal Gain Bandwidth Chart:

Gain	Minimum 3db Bandwidth
0db	1-70 Mhz
20db	1-70 Mhz
40db	1-10 Mhz
60db	1-10 Mhz

Absolute Gain Tolerances :
1db insertion loss maximum at 0db, +5/-1db tolerance at 20, 40, and 60db (absolute gain variation from unit to unit must be less than 2db)

Gain vs. Temperature :
less than 0.5db variation over 25-40 degree Celsius range at any gain setting

Gain vs. Power Supply :
less than 0.5db variation for +-10% power supply variation from nominal at any gain setting

Gain Switching :
less than 20 millisecond switching time

Gain Repeatability :
better than +-0.05db at any gain setting for >100,000 operations

Gain Control :
two to four inputs, any dc control voltage plus or minus 5 to 24 volts

Input VSWR :
less than 1.5:1 over 1-70 Mhz range at any gain setting

Input Power :
withstand +4/-2 volt peak inputs (1-100 Mhz) without damage, 0db setting must operate according to spec up to this level

TABLE 3 con't.

Output VSWR :
less than 1.5:1 over 1-70 Mhz at any gain setting (including 75-100 ohm dc path to ground at the output)

Output Power :
1db compression point greater than or equal to +13dbm over bandwidth at any gain setting

Operating Temperature :
20-60 degrees Celsius

Storage Temperature :
0-100 degrees Celsius

Connectors :
input - SMA female, output - type N female

Dual Channel Matching

Gain Match :
better than 0.1db at any gain setting over 25-40 degree Celsius range at three checkpoints - 2.35 Mhz, 6.30 Mhz, and 48-58 Mhz band

Insertion Phase Match :
better than 3 degrees at any gain setting over 25-40 degree Celsius range at three checkpoints - 2.35 Mhz, 6.30 Mhz, and 48-58 Mhz band

IV. BEAM POSITION ANALOG PROCESSORS

1. General description

The function of the beam position analog modules is to convert amplitude information into bandlimited d.c. levels appropriate for digitization. Two d.c. levels are supplied, one is proportional to the beam intensity, and the other is proportional to the normalized beam position.

Two separate beam position modules are used, the r.f. module processes wideband 53 Mhz signals, and the low frequency module processes narrowband, low level, 2.4/6.3 Mhz signals. The design considerations for both of these modules are discussed in this section.

The r.f. module has been designed to handle turn-by-turn position information which will be the primary mode of operation during the accelerator commissioning. During turn-by-turn measurements, the signal is generated by 80 bunches of protons circulating in 53 Mhz buckets. The rf module will also be used to measure the antiproton extraction orbit in the Accumulator. The other mode of operation, for the r.f. module, is during extraction of antiprotons from the Accumulator. During extraction, the signal is generated by a batch of antiprotons seperated by the revolution period. Each batch contains 13 bunches of antiprotons spaced in 53 Mhz bucckets.

The low frequency module is designed to handle the narrowband, low level signals produced by antiprotons in closed orbits in both the Debuncher and the Accumulator. The low frequencuy module operates on a single harmonic of the periodic signal which is generated by either a gapped beam, beam Schottky noise, or modulation produced by the r.f. stacking system. The Debuncher system is designed to operate on the 4th harmonic of the revolution frequency (2.36 Mhz) and the Accumulator system operates on the 10th harmonic (6.28 Mhz).

2. R.F. beam position module

The r.f. module is a modified version of the Saver r.f. beam position module. Since operation of the Saver module has been discussed elsewhere, only the modifications will be discussed here.

Figure 14 shows the block diagram of the modified r.f. module. The r.f. module was originally designed to process signals coming directly from the beam position plates. The modifications described here, allow the processing of the sum and difference signals coming from the tunnel preamps.

2.1 Modifications

There are two modifications which are made to the existing r.f. module. The first change, involves changing the tap off point for the coherent detector. The input to the coherent detector is now derived from a power splitter in the sum signal path. A similar power splitter remains in the difference signal path only to equilize delay and amplitude variations in both paths.

The other change occurs in the am/pm converter. The change involves replacing two of the in-phase power combiners to quadrature combiners. This change is necessary to produce a 90 degree phase difference, at the output of the am/pm converter, when the difference signal is zero (centered beam).

3. Low frequency beam position module

This module is designed to handle the low level signals encountered during the antiproton storage process. Figure 15 shows the block diagram of the module. Since the signal to noise ratio, at the output of the preamps, is so low, a heterodyne scheme was chosen so that the system bandwidth could be made as narrow as possible consistent with the information bandwidth of interest. The incoming signals are down converted to an intermediate frequency of 10 Khz where filtering and detection are more easily accomplished. The module is designed to operate over a 46 dB dynamic range from 1mV rms to 200 mV rms.

3.1 Preselection filters and mixers

The purpose of the preselection filters is to reject undesired harmonics of the beam signal. This minimizes spurious responses which would occur in the mixing process. A simple resonant circuit should be adequate for this filter.

The mixers are standard level, double balanced mixers. The conversion loss is typically 6 dB for local oscillator drive of +7 dBm. The 1 dB compression of the mixer is at -1 dBm or 200 mV rms.

The filter and mixer combination must be amplitude and phase matched to within 0.5 dB and 2 degrees respectively. The filters can be used to compensate for slight differences in the two mixers.

3.2 VCXO

The Debuncher and Accumulator each have one VCXO which supplies local oscillator power to all 12 low band modules, for that ring. The oscillator frequencies are selected to be approximately 10 Khz above the calculated harmonic frequency of interest. The frequencies are 2.3701 Mhz plus or minus .03% for the Debuncher and 6.2981 Mhz plus or minus .05% for the Accumulator. The Accumulator VCXO has a wider frequency tuning range to allow coverage of the injection and core signals. The oscillator that will be used is a Greenway, ovenized, VCXO with a long term frequency stability of 0.6 ppm for the 2.3701 Mhz oscillator and 0.8 ppm for the 6.2981 Mhz oscillator over the temperature range from 0 to 50 degrees centigrade.

A 10 bit DAC is provided to digitally control the oscillator frequency. The control voltage can be set or read by the BPM microprocessor via the external device bus.

The VCXO output is amplified and applied to a 3 way power splitter for distribution to each service buiding. At the service building another 2 way splitter divides the signal for distribution to racks located on both ends of the building. At each rack, the signal is attenuated and split again for application to the horizontal and vertical low frequency modules.

3.3 I.F. Filter and amplifier

The i.f. filter is an op-amp active filter which realizes an inverse-chebyshev magnitude response. This response was chosen because of its rapid roll-off and notch characteristics. The need to measure the injected beam in the presence of the core, means that a minimum of 40 dB of rejection is needed at approximately 2.3 Khz below the center frequency of the filter (the frequency which corresponds to the core orbit offset). Other requirements of the filter are, a 1 dB bandwidth of 1 Khz and a gain of 10 dB. In addition, the two filters must be amplitude and phase matched within the passband to 0.5 dB and 2 degrees, respectively.

Figure 16 shows the schematic of the filter presently under study. The design allows non-interactive tuning of each filter section. This greatly simplifies the adjustment procedure. Figure 17 shows the calculated response. This response has been measured and was found to agree very well with the calculated curve. The match of two separate filters has been measured at room temperature and was found to be within 0.2 dB and 2 degrees across the passband. This can probably be improved by more adjustment.

Another concern for the filter is that the equivalent input noise be well below the minimum rms noise level expected from the preamps. The equivalent input noise for this filter has been measured to be below 10 microvolts rms. This is more than adequate.

3.4 Position detector

The performance of the position detector is key to the overall system performance. The detector sets the minimum signal to noise ratio required for a given position resolution. A simultion program was written to investigate the characteristics of various detector schemes in the presence of large noise fluctuations. All detectors studied so far have exhibited a gain compression which forces the d.c. output towards a circuit minimum as the signal to noise ratio tends to 0.

Of the various detector schemes studied so far, the am/pm converter scheme used in the main ring r.f. module seems to work the best. In this scheme, the choice of phase detector has a major impact on the noise threshold of the detector. A simple XOR gate phase detector outperforms other phase detectors that were studied. Figure 18 shows the measured position error versus signal to noise ratio for an am/pm converter using an XOR gate phase detector. For a position resolution of 1mm, the minimum signal to noise ratio is 15 dB.

Another advantage of the am/pm converter is its large dynamic range. Greater than 40 dB of dynamic range is readily achieved in such configurations.

The position signal appearing at the output of the low frequency module will have a plus and minus 2.5 volt swing consistent with the r.f. module. An additional output amplifier will provide a 50 ohm drive capability.

3.5 Intensity detector

This detector is a lower resolution detector which gives a d.c. output which is proportional to the sum signal amplitude. An anlog multiplier will be used to square the sum signal. The output of the multiplier is then filtered to obtain the d.c. signal, and an output amplifier provides the 50 ohm drive requirement. The intensity signal appearing at the output will have a 0 to -2.5 volt swing consistent with the r.f. module.

4. Input multiplexer

A beam position module can service up to 10 different beam position plates via the input multiplexer. The input multiplexer module accepts up to 10 sum and difference signals (in the case of the accumulator there are only 8 sets of vertical plates serviced by each vertical multiplexer and 7 sets of horizontal plates serviced by the horizontal multiplexer). The multiplexer communicates to the bpm microprocessor via the test signal generator module. This module contains the interfacing logic to the external device bus.

This multiplexer module is a modified version of the multiplexer module which is used in the main ring system. Minor modifications need to be made to the existing module design to provide the proper 50 ohm termination.

5. Position gain and offset module

This module provides additional signal conditioning and switching after the signal has been processed by the position modules. Communication to the bpm microprocessor is via the external device bus.

This module performs signal averaging and provides programmable magnification and offsets which are controlled by the bpm microprocessor. Signals coming from either the r.f or low frequency module can be averaged to reduce uncorrelated signals. Figure 19 shows the block diagram of this module.

5.1 Sample and hold amplifier

The sample and hold amplifier samples the wide band signal coming from the r.f. module. The sample time is controlled by a comparator which looks at the intensity signal. A sample is initiated on the downward edge of the intensity signal which corresponds to the leading edge of a batch of protons approaching the beam position plates. In this way, the average is taken only over the time when a batch of particles is present between the plates.

5.2 Analog switch

The analog switch selects which position and intensity signals are to be averaged by the low pass filter. The switch selects signals coming from the r.f. module or the low frequency module.

5.3 Position offset and gain amplifier

This amplifier provides a programmable offset and gain for the position signals. The offset and gain are provided for both the wideband and narrowband signal however they are not independently controlled. Also, there is no provision for an offset in the vertical signal path. The position offset is provided to allow centering of the position signal within the ADC window. The position gain is provided to allow magnification.

5.4 Low pass filter

The low pass filter performs averaging and noise reduction of the position and intensity signals. The bandwidth of the filter is programmable to 75, 200, 500 and 1000 Hz.

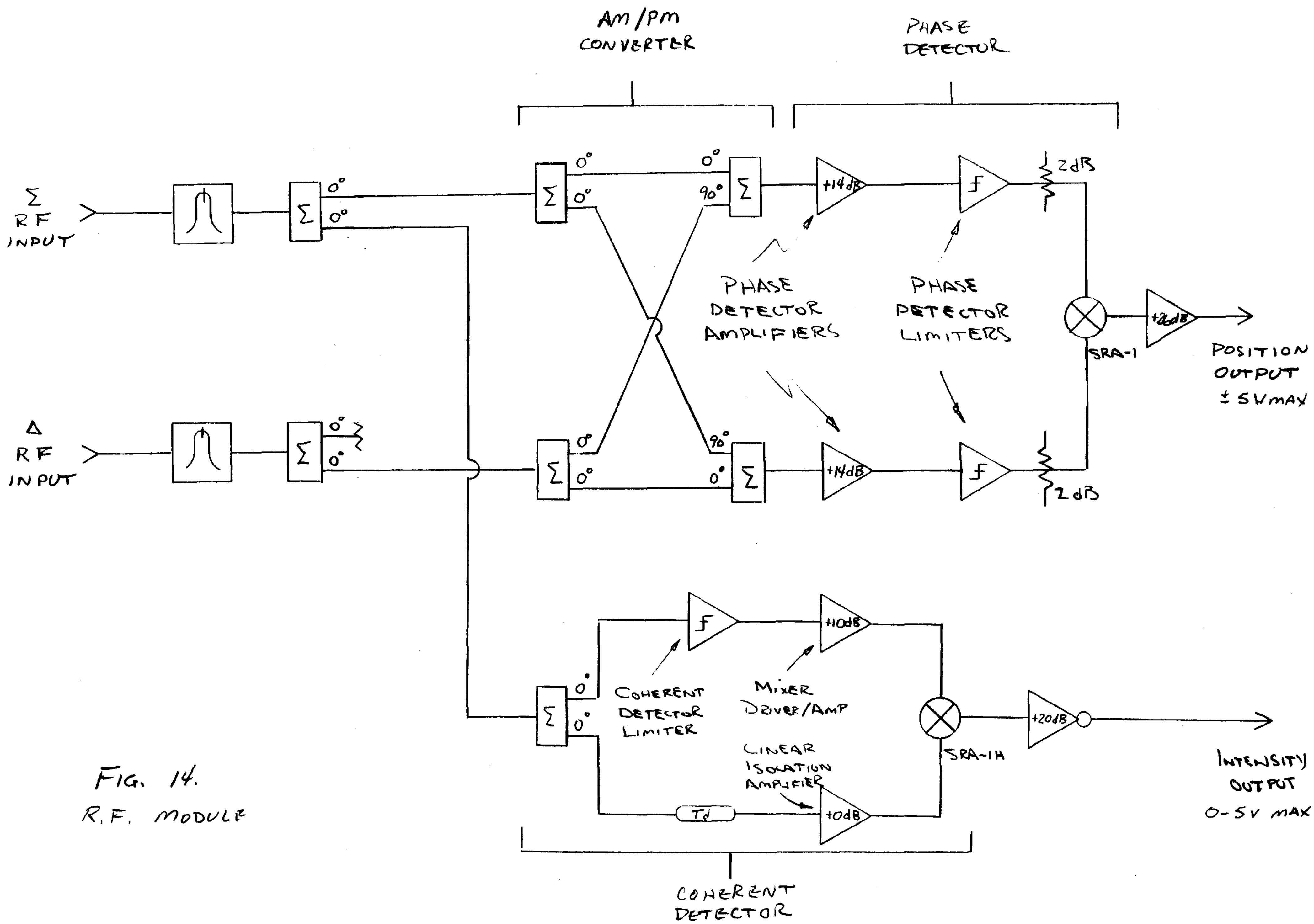


FIG. 14.
R.F. MODULE

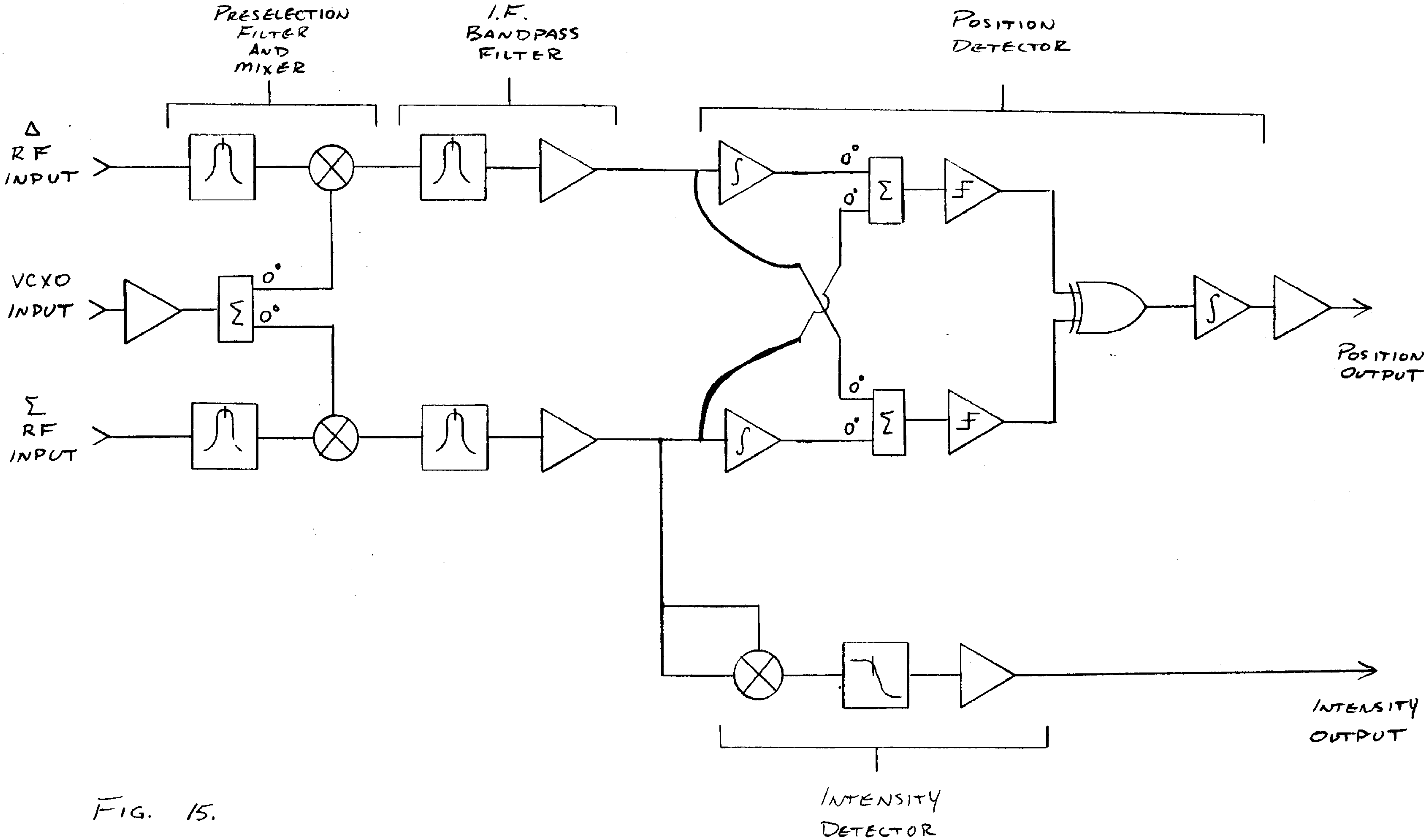


FIG. 15.
LOW-BAND MODULE

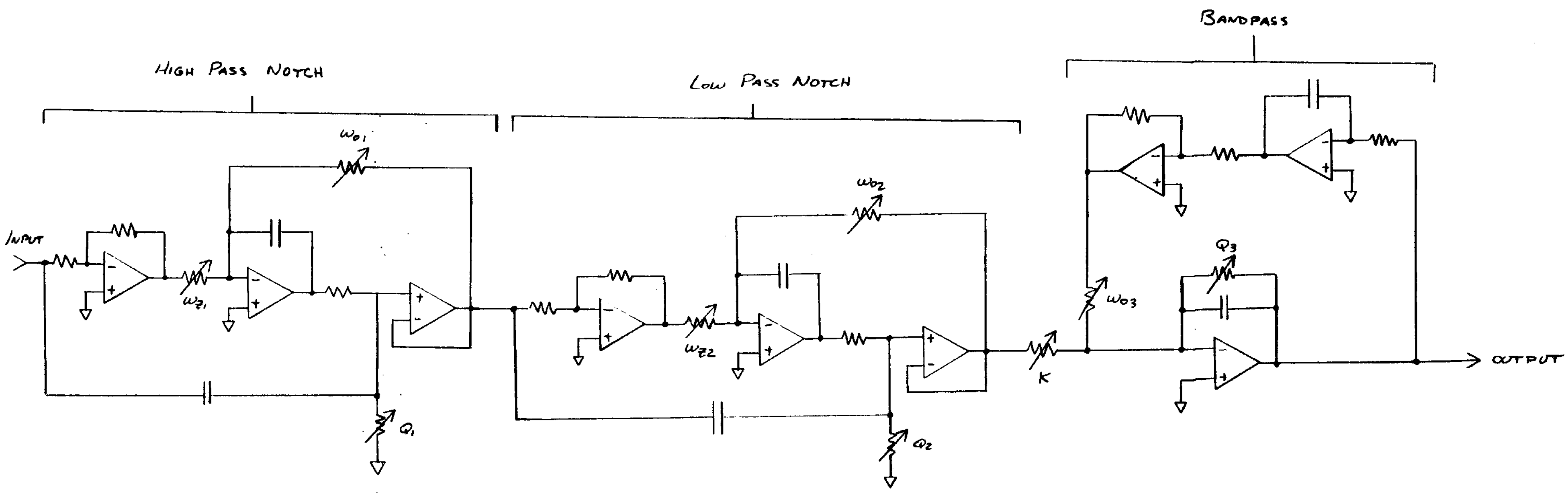


FIG. 16.

I.F. BANDPASS FILTER

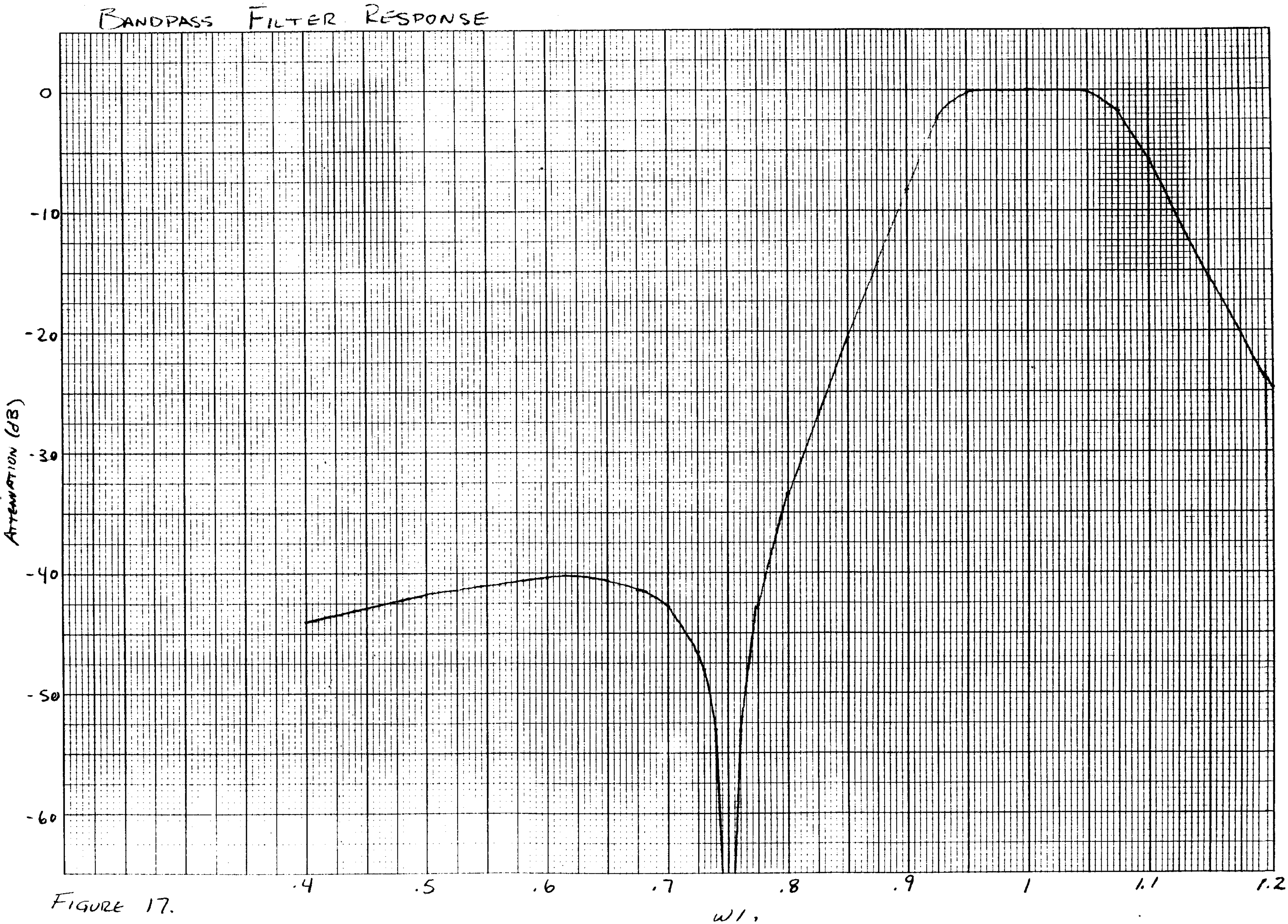

BANDPASS FILTER RESPONSE
0
-10
-20
-30
-40
-50
-60
ATTENUATION (dB)
.4
.5
.6
.7
.8
.9
1
1.1
1.2
w1,

FIGURE 17.

$\frac{x}{a} = 2\frac{\Delta}{\Sigma}$

CALCULATED POSITION $= 2 \tan\left[\pi/4\left(1-(\bar{V}_o - .133)/1.682\right)\right]$

ACTUAL POSITION $= 2 V_A/V_\Sigma$: ERROR $= \frac{\text{ACTUAL} - \text{CALCULATED}}{\text{ACTUAL}} \times 100$

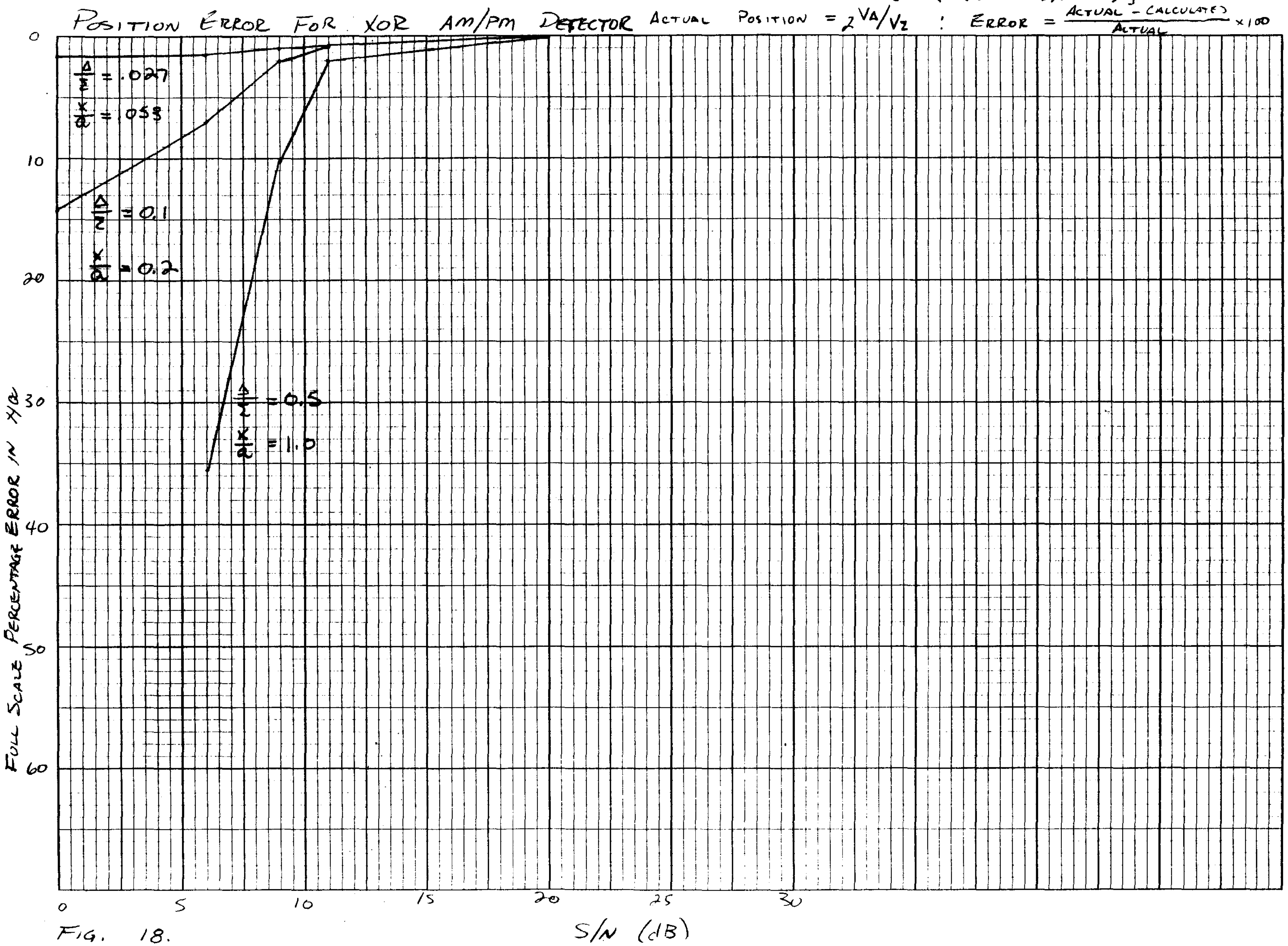


FIG. 18.

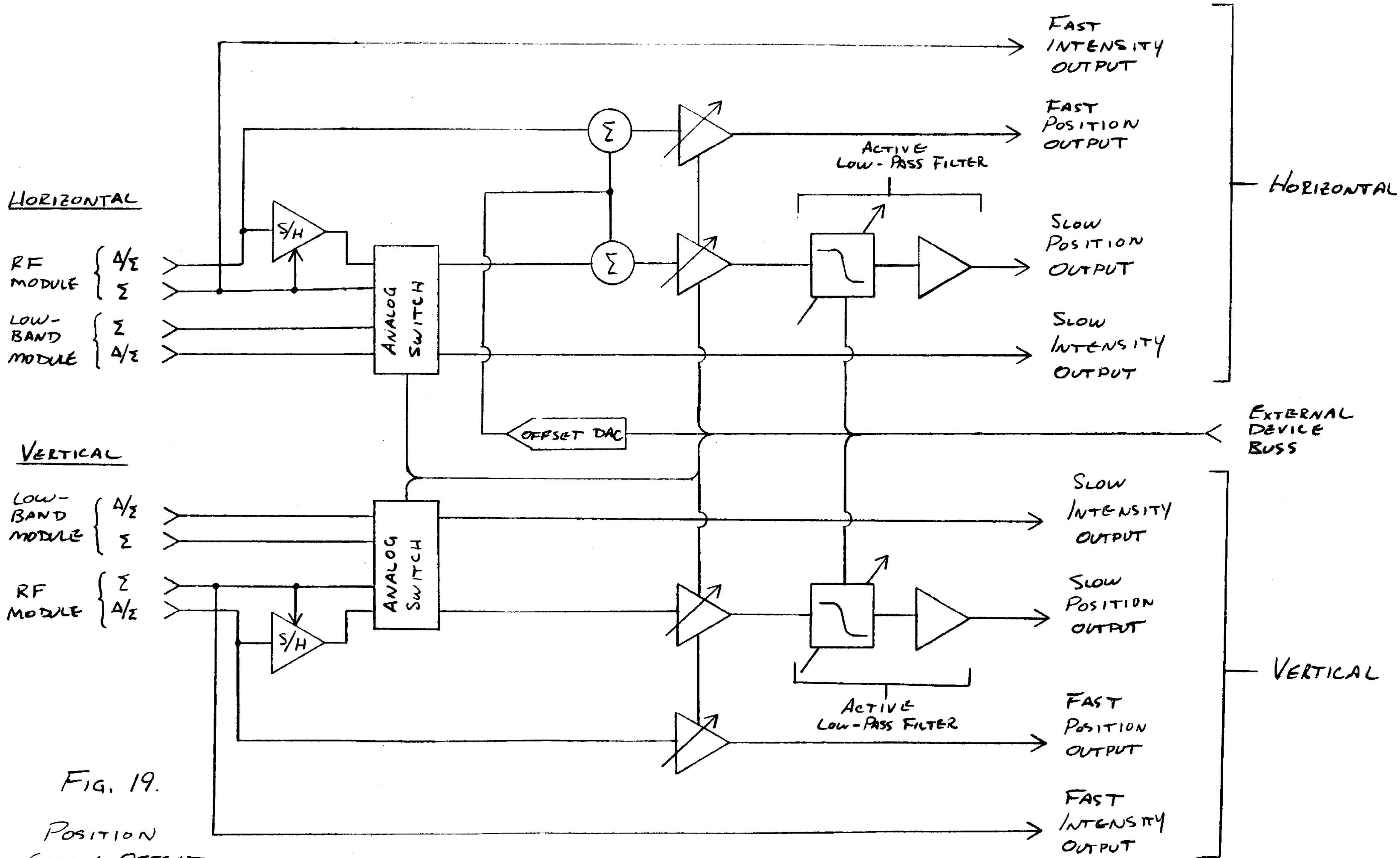


Fig. 19.

Position Gain & Offset Module

V. SYSTEM OPERATION AND CONTROLS

The layout of the complete BPM system has been given in Figure 1. Sum and difference signals from each position monitor are processed through gain switchable amplifiers within the tunnel and are then received in the service buildings through a modified version of the Main Ring multiplexer. Twelve service stations of the type shown in the figure exist in the total system--six each in the Debuncher and Accumulator. Each station handles both the horizontal and vertical position monitors for one sixth of one ring. This implies ten BPM's per multiplexer in the Debuncher and seven/eight per vertical/horizontal multiplexer in the Accumulator system. Following the multiplexer position and intensity signals are generated through both the high and low frequency systems described in Section IV. The fast (53MHz) position and intensity signals are then sent to a fast A/D converter which communicates with the Saver Turn By Turn card in a multibus crate. Multiturn orbit measurements are digitized through the Saver Analog Box operating in Flash Mode. Only two of a possible twelve daughter cards are actually present in the Analog Box. Input to the Analog Box is selected from either the high or low frequency detector. Provisions are made for both magnifying and offsetting the position signal in order to utilize more effectively the eight bit resolution provided by the digitizers.

The multiplexers need to be able to switch inputs at speeds measured in milliseconds. This is because for multiple turn measurements in which bandwidths of 1KHZ are used one must wait several (or even tens of milliseconds) for the input levels to the analog box to stabilize once a change is made. For measurements which utilize digital averaging to improve resolution it will be necessary to cycle through the multiplexer 100-200 times during the course of a measurement. For a measurement of the antiproton core for example, a bandwidth of 70Hz is chosen. If 256 measurements are taken at each of eight multiplexer positions the entire measurement period lasts 60 seconds. Note that for the Debuncher coasting beam we should be able to make approximately 100 measurements at each pickup during the 2 seconds the beam is present on each cycle.

Special provisions have to be made for triggering the Analog Box in flash mode since the narrow bandwidth of the multiple turn system precludes any rapidly changing intensity signals entering the box. Flash mode will be initiated by a software generated lowering of the preset intensity threshold within the box at a specified time. The fast A/D will be self triggering on the intensity signal. The bandwidth of the high frequency system is about 5MHz. This means that the associated time constant is 32nsec, or 1.7 bunches. In order for the trigger circut to be able to recognize a gap in the beam, and hence distinguish subsequent turns, approximately eight empty bunches are needed.

A great deal of flexibiltiy is built into the system as a consequence of the need to detect and measure circulating beams with vastly different characteristics. Among the parameters of the system which are variable are,

1. Pickup Signal Level: Switchable between either 0db(normal) or 40db attenuation through a capacitive divider at the preamp input.

2. Tunnel Switched Gain Amplifier: Variable gain between 0-60db in 20db steps.

3. Multiplexer Cycle Pattern

4. Oscillator Frequency: In the low frequency detector. Variable over +.05%.

5. Position Gain and Offset: Gain x 1,2,4 and seven offset positions.

6. Filter Bandwidth: Variable 75Hz to 1000Hz in four steps.

7. Test Signal Generator: Generates difference and sum signals for monitoring scale of offset of position measurement.

All control of variable parameters is through the multibus External Device Bus.

Each multibus crate is controlled by an 8004 microprocessor and an associated M080 processor which handles communications to the host computer through CAMAC. The multibus crate used is identical to what is used in the Saver BPM system except for the addition of a Fast Access Board needed to control the fast A/D. As mentioned earlier we intend to make use of existing software to the fullest extent possible.

VI. Testing and Self Diagnostics

A test signal generator module, shown in block diagram form in Figure 20, will be located at each of the 12 BPM signal processing stations in the service buildings. It will be able to inject rf signals of programmable amplitude at both 6.3 MHz (2.4 MHz in Debuncher) and 53 MHz into the test signal inputs of the preamplifiers. The test generator will be under the control of the BPM microprocessor system via the external device bus.

The purpose of the system is to provide a means of checking the gain, common mode rejection, and general integrity of each position monitor channel from the preamp through the entire signal processing chain. The test generator will also be able to inject signals directly into the analog multiplexers to check service building equipment independent of tunnel electronics. The testing system will prove valuable during the initial BPM system set-up and testing, and later as a trouble shooting aid. Certain automatic testing procedures can be programmed to run on a regular basis to track any sensitivity and offset variations of the beam position monitoring electronics. The information gained will allow generation of a look-up table of detected errors to be used to correct actual beam measurement data.

The test signals will be daisy chained from one preamp to the next on RG58 cable over about one sixth of each ring. Attenuation in the cable will result in something like 10dB signal variation between the nearest and the most distant preamp at 53 MHz. The absolute signal level is only of secondary importance when measuring the relative gains and balance of the sum and difference channels of a single amplifier string. The actual signal levels are important when trying to determine absolute amplifier gains and noise. This might be necessary to allow for correction of position measurements at very low signal levels when the signal to noise ratio gets worse than 15dB in 1 KHz in the low frequency beam position module. One time signal level measurements and cataloging will be done to establish the relative signal levels down the daisy chain. Four different signal levels at each frequency will be selectable to allow testing the amplifiers at each possible gain setting.

TEV I BPM TEST SIGNAL GENERATOR

FUNCTIONAL BLOCK DIAGRAM

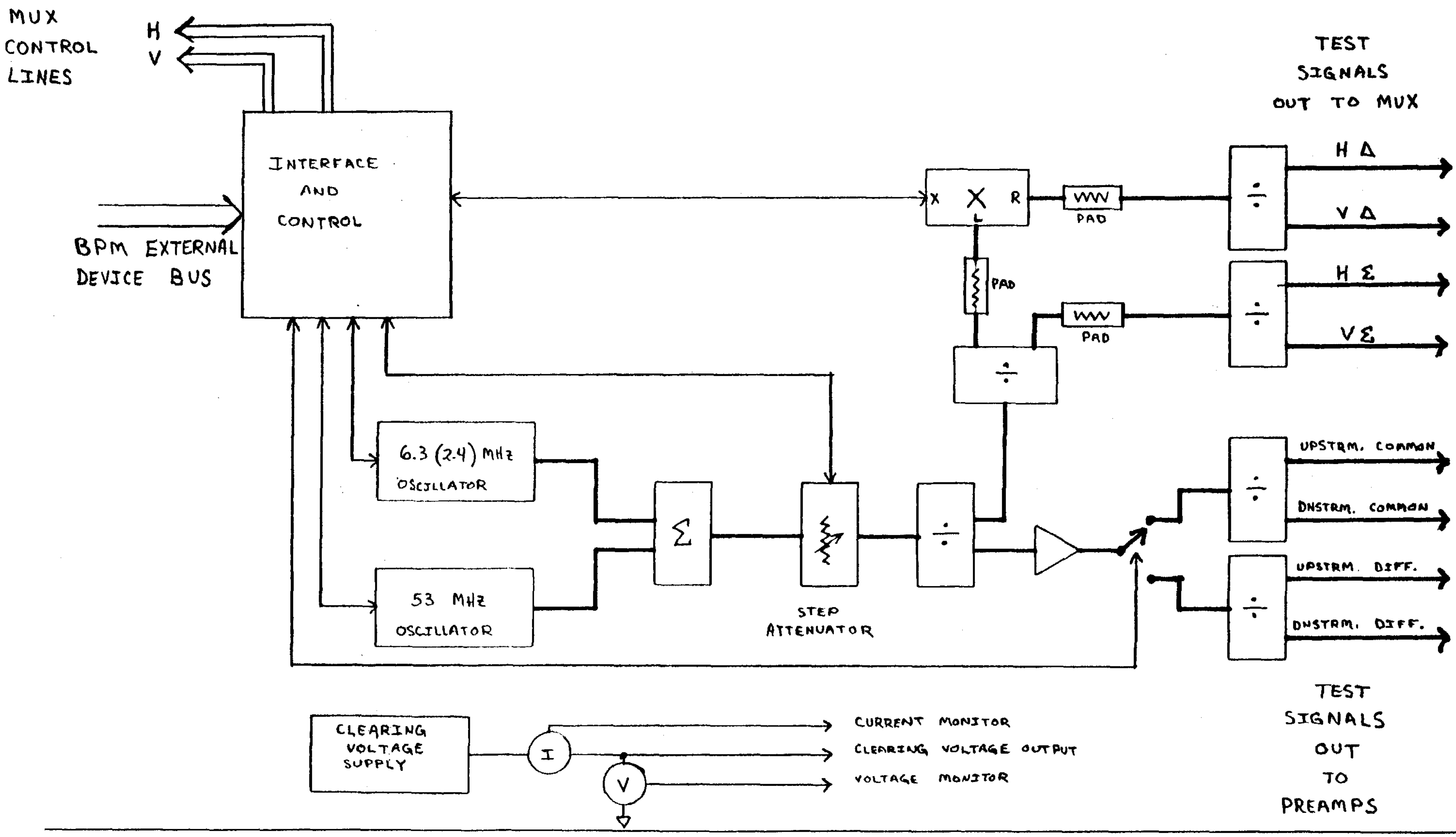


FIGURE 20