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BEAM POSITION MONITORING

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Preface

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The information contained in the following section consists of two parts. The first part describes the prototype Tevatron position monitor system which is being used in the Sector Test. The second part briefly discusses a possible system for independently monitoring a pair of counter rotating p and $\bar{p}$ beams which might not have a repetitive 53 MHz structure (i.e. only a small number of bunches spread out around the machine). The properties of these beam detectors are summarized in Appendices I and II.

The design specifications for the system were:

1) Sensitivity to tuneup beam of 30 bunches each having 5×10^7 protons with 53 MHz structure.
2) Maximum intensity 1×10^{14} in machine (i.e. 1×10^{11} per bunch)
3) Very low heat load to cryogenic system (<<1 watt per position monitored).
4) Very high radiation resistance (3 megarad total dose).
5) Position output linear over a range of ±15 mm, limits at ±18.5 mm.

Part I

A beam position monitoring system has been developed for the Doubler Accelerator to determine the orbit in both the radial and vertical planes. This system will aid in tuning, monitoring during normal running, and in developing the necessary startup and diagnostic routines for the Doubler machine.

The system developed for the Doubler is composed of four principal parts: (1) electrostatic pickup assemblies installed in the beamline at each quadrupole location, (2) a low-loss, low noise cable system to convey the beam-induced pick-up signals to the nearest service buildings (3) an electronic equipment module located in each service building which will accept the pick-up signals and which will contain devices to multiplex the rf quantities, derive the normalized position values, detect the presence of the beam for timing, triggering, and data use and an interface device to permit data quantities to be efficiently matched to a general dataway, and (4) computational/control/display components located in the main control complex to read out and display the gathered data and to permit operator/machine interactions with both accelerator and beam monitoring devices.

The orbit monitoring system devised for the Doubler allows the vertical and radial orbits to be determined at any specific time during the Doubler machine's cycle, from injection-to-extraction. The doubler monitor system also permits some of the customary diagnostic features found so useful in the main synchrotron to be retained, i.e., time plotting of orbit position for a selected azimuth, and a go, no-go test of the major monitor system components.

The Doubler beam monitor system also contains provisions for operation under special low-intensity conditions in a mode designated as Fractional Batch Single Turn, (FBST). In the FBST mode, the total injected charge will be reduced by a large factor and only about 32 or so bunches, normally spaced to retain the rf fundamental component, will remain to act as a "pilot" beam. Measurements of beam position based on the "pilot" will permit low-intensity orbit tuning to be accomplished thereby reducing the possibility of beam-induced magnet quenches. The first passage of the "pilot" beam through a set of pick-up electrodes will be detected, processed for position, stored and accumulated over several cycles and thereafter displayed for tuning and/or diagnostic use. It is expected that these data will be instrumental in the initial correction of anomalous orbits and in establishing those control settings of machine variables which will give the "best" orbit.

This report will contain a general outline of the major technical considerations relevant to the beam monitor system, will give a brief description of the principal components, will comment on devices already in prototype form.

General Considerations

Many interrelated factors govern the overall equipment designs for the beam monitor system. Some however, predominate in establishing the general parameters. Factors such as (1) operations dynamic range, (2) speed of response for the FBST mode, (3) cyrogenic impact on beam pickup design, (4) the hostile environment of the service buildings, (5) ways to make the collected data useful for operator use, and (6) single or dual beam operation have been the most significant factors. These are reviewed below.

<u>Operational Dynamic Range</u>

The input signal derived from the beam pickup is expected to vary in amplitude over relatively narrow limits, say 10 db (3:1) during normal doubler operation, but during the tuning processes or during diagnostic conditions, only a very low intensity will be used. The lower bound intensity, which has the most impact on dynamic range, can be evaluated from the following:

At design intensity of 5×10^{13} ppp and with at least 82 of the 84 buckets/batch filled and for 13 batches present in the main synchrotron, the bunch density is:

$$\frac{5 \times 10^{13} \text{ ppp}}{82 \times 13} = 4.7 \times 10^{10} \text{ protons/bunch.}$$

This per-bunch intensity is more than an order-of-magnitude more than the total maximum envisioned (3×10^9 protons total) for Doubler tuning and diagnostics under the FBST mode. One method to reduce the beam intensity to the Doubler is to allow the main synchrotron to spill most of its beam prior to injection. In this case, the beam remaining could act as the "pilot" beam for the FBST mode. At present, the main synchrotron operates normally during slow spills to at least 1% of a 1×10^{13} ppp beam; this represents a 40 dB lowering of intensity or a 54 dB reduction based on the design maximum intensity of 5×10^{13} ppp. The factor of 5 between the above levels corresponds to 14 dB. For a reduction of 54 dB, the attenuation value is $10^{54/20}$ or 501. The bunch intensity resulting by spilling and thereafter injecting at the attenuated level is therefore,

$$\frac{4.7 \times 10^{10}}{501} = 9.4 \times 10^{7} \text{ p/bunch.}$$

In order not to exceed a total of 3×10^9 protons circulating under the FBST tuning conditions, only N bunches could be injected where,

$$N = \frac{3 \times 10^9}{9.4 \times 10^7} = 32 \text{ bunches total.}$$

Thirty-two bunches, each having 9.4×10^7 protons would appear reasonable from the signal processing viewpoint assuming that the rf fundamental component (53.1 MH) remains as it sould for normal batches, i.e., that the beam is bunched as it normally is at higher levels. The 32 bunches represents about 1/3 of the normal bunches contained in a batch.

The operational dynamic range value can now be established by taking into account the 54 dB range and allowing a reasonable additional value, say (6 dB), to be included to account for beam modulation effects. This additional range would permit processing bunches with intensities of about 5×10^7 protons per bunch, on the average. Using the accelerator related 54 dB and the 6 dB for modulation effects, a design dynamic range value of 60 dB minimum is established.

Speed of Response

The FBST mode of operation poses the most stringent requirements on data collection speed. In this mode the normalized position value, $K \left(\frac{A-B}{A+B}\right)$, must be determined within the time span of the available bunches, while beam presence must be determined more rapidly, say within the first half-cycle of an rf wavelet (10 ns), and other functions associated with data collection in the range of 10 to 100 or so ns. For 32 bunches the total signal interval at 53.1 MHz is,

$$\frac{32}{53.10 \times 10^6} = 603 \text{ ns.}$$

To assess the impact of this value, measurements were conducted of candidate (non-superdamper type) components, These measurements indicated that about 300 ns would be needed for rise, fall, and settling time budgets and about 300-to-350 ns would be required for processing time during the "constant" part of the signal wave. The 32 bunches therefore appear just adequate for ordinary devices such as moderate cost operational amps, FET switches, diode arrays, doubly balanced mixers, filters of various common types, and TTL logic devices. One factor however, normalization of the intensity variations, precludes the use of such circuits as differential operational amplifiers, differencing feedback dividers, or operational dividers as the principal processing circuit. The reason is that these circuits are much too slow and do not operate over a sufficiently large range, (60 dB). As a result, an rf-to-phase conversion system with Limiting and Phase detection was chosen to process the wide range of signal data. A processing speed of one rf period, i.e., 18.8 ns is achievable with these circuits.

Within the guidelines of the above and from associated general circuit considerations, the following processing speeds were established.

Equipment or Function	Mode	Speed of Response Required
Beam Position Units	FBST	150 ns rt/ft, 300 ns flat
Beam Trigger Unit	FBST	TTL speed; 10 ns rt/ft
Data Interface Unit	FBST	150 ns rt/ft <300 ns acquisition time
Normalization	FBST	1 rf period; 18.8 ns
Gate Functions	FBST	<10 ns edge speed rf gate interval adjustable over 300 ns
Analog Switching	FBST	10 ns on-to-off
Analog Settling	FBST	150 ns max.

Other modes of operation require equal or less responsiveness.

Cryogenic Impact on Beam Pickup Design

The beam pickup is an integral part of the Doubler quadrupole magnet assembly. In particular, it is the quad spool assembly and is surrounded by a vacuum box. It shares beamline space in the spool assembly with other devices at 4.2° Kelvin. Each of the pickup electrodes are attached to the vacuum box interior via 2 hermetic seals, one at the cold beamline vacuum wall and the other at a type "N" receptacle, mounted to the warm vacuum box wall. (see Fig. 1). The beam induced signal is transmitted from the cold region to the warm via a twistline. The twist-line wire is made of ADVANCE metal, a copper nickel alloy having a thermal conductivity lower than copper by a factor of $\sim$300. Electrical impedance matching networks consisting of a 50 ohm damping resistor and an rf inductor at the 4.2°K end of the line permit operation at low VSWR; in the order of 1.1:1. Elements for the vacuum feedthru, balun, twistwire line, and damper resistor, were selected on the basis of repeated tests for survival and parameter constancy when operated at 77°K and 4.2°K. The mechanical design of the pickup incorporated measures to reduce damage via localized stress buildup upon cool down/up. These measures, allowing the central plate and support to "free float", attachment of electrical connections via flexible soft leads, use of spring finger pin sockets, the selection of pottants with matched thermal expansion coefficients, and the use of pure cotton or glass-fiber materials for strain relief, all were aimed at safe-guarding the device under cooling or heating stress.

Since a physically small device permits minimum loading of the spool cryostat and saves valuable space for other devices, the smallest possible length is sought. This length was established by determining the peak beam current for the lowest level design bunches and the beam pickup mutual impedance for candidate lengths and designs. The peak beam current for the least intense bunches, assuming a 4 ns bunch length, is:

$$I_{pk} = \frac{dq}{dt} = \frac{5 \times 10^{7} \times 1.6 \times 10^{-19}}{4 \times 10^{-9}} = 2.0 \text{ ma. pk.}$$

Experience has shown that beam signals (at the pickup) of 1 mV, P-P/50Ω approach the boundary where spurious noise effects, not thermal noise, begin to create processing errors. Therefore at bunch intensities of 5×10^7 protons/bunch it is desirable to produce a signal at least 1 mV P-P/50Ω, and perhaps more than this by a factor equal to the worst-case cable attenuation value, 10 dB, a numeric factor of 3.

It is desirable to allow the pickup length to grow until at least 3 mV, P-P/50Ω is available with lowest bunch intensity. Measurements of several candidate pickup configuration were made to determine the mutual impedance parameter. The device selected (a parallel plate type) provides a value of 1.25 mV/ma, Pk/50Ω for a 5" long x 2.9 " wide electrode spaced about 0.25 inches from the beamline wall. With a minimum current of 2.0 ma peak. this device produces 1.25 x 2.0 = 2.5 mV Pk/50Ω or 5.1 mV P-P/50Ω at the lowest expected signal. The parallel plate device was therefore chosen as a candidate because of the performance margins and its relatively short length. One half inch of outerbody length at each end of the plate was added to the pickup for attachment, making the total pickup a 6 inch long x 3.5 inch diameter device. These dimensions are compatable with current space allocations for the detector. Should increased beamline space be available a more serious review of other devices would be necessary. The aperture spacing between plates for the device is relatively large, 2.5 inches, thus minimizing impact on beam coupling and dynamics in the pickup region.

Hostile Environment of the Service Buildings

Most of the beam signal processing equipments are located in the service buildings distributed about the main synchrotron. Three factors associated with these buildings have impact on the design of equipment in them: (1) the buildings have extremes of ambient temperature, from about -20°C-to-+50°C, with high relative humidity possible. (2) dust and large particle-size contaminants such as insects are prevalent and (3) large ac and dc electrical currents are present, together with large current switchgear for magnets, rotating equipment, heaters, compressors, etc. Equipment designs for the beam monitors use MIL spec devices to aid in reducing the effects of this environment on reliability. All modules are shielded so as to reduce transient noise effects. Additional precautions in this regard include shielded NIM bins, and consolidation of beam monitoring devices in designated, "quiet" rack assembly. High current ac and switching devices are excluded from this rack. Forced air cooling is arranged so that air inlets are not choked off due to dust and particle buildup.

Data signal and low-level rf signal lines enter thru "N" type bulkhead connections via an insulated mounting panel so as to reduce the effects of local ground currents within the cabinet.

Data Collection and Operator Use

As data is processed by the equipment in the service buildings, the interface unit will transmit it to controls instrumentation where it will be digitized and sent via cable to the Control Room. Here operators will be able to interact with both data gathering devices and machine parameters.

Data display for selected modes of operation can be directed from a console keyboard and from the same keyboard machine parameters can be manipulated for optimization. Hard copy of displayed information can be obtained for use in diagnostics and record keeping.

Dual Beam Operation

Both p and $\bar{p}$ beams may be present simultaneously in the machine. Under these conditions the orbit monitor will require beam sampling via isolated coupling devices in the beamline or other means to separate data quantities. Dual beam sensing is discussed in section II and one type of processing technique outlined.

Beam Monitor Units

The following section contains a brief description of the monitor units. Information is arranged as follows:

1. Beam pickup
2. RF cable system
3. RF Multiplexer
4. Service building electronics, including position module, beam trigger unit, and data interface unit.

1. Beam Pickup

The beam pickup is shown in Fig. 1, DWG MD106357. The device is 6" in length and constructed of heavy wall stainless tubing. The 5" long plates are attached to an 8 sided G-10 insulator which is positioned with respect to the feedthru by a locator bar assembly (see Fig. 2). Signal leads from the plates pass thru a ceramic/metal hermetic seal, detail in upper right Fig. 2, and attach to a small circular PC board. The 49.9Ω damping resistor and balun coil are mounted to the PC board which is detachable via the pin socket. The twistline assembly carries the signal to a type "N" bulkhead connector for attachment to the vacuum box wall. The following general requirements apply to the pickup assembly.

<u>Frequency Range, Bandwidth</u> - The beam sensor operates throughout the frequency band from 10 to 100 MHz. For beams of 1-to-10ns width.

<u>Nominal Repitition Rate</u> - The beam sensor operates with particle beam bunch rates in the range from 50 to 55 MHz.

<u>Characteristic Impedance</u> - The beam sensor has a characteristic driving impedance of 50 ohms, nominal. This impedance to be determined by RF reflectometer or equivalent means looking into the output signal port.

<u>Voltage Standing Wave (VSWR)</u> - The beam sensors VSWR is less than 1.15 over the 10 to 100 MHz range. This requirement is established at the output signal port.

<u>Plate Electrode Impedance, Terminated</u> - The plate electrode impedance is nominally resistive following the attachment and termination of the twistline transmission line. The impedance between the outer body and the individual separate plates is

25 ± 5 0 ‡ 10° ohms at 20 ± .1 MHz

and

27 ± 5 5 ‡ 10° ohms at 50 ± .1 MHz

Line termination = 50Ω at output port

<u>Beam Intensity Level</u> - The beam sensor operates without damage at proton beam intensities of 5×10^{13} protons/bunch.

<u>Electrical Sensitivities</u> - The beam sensor meets the following requirements for electrical sensitivity.

a) <u>Directional Sensitivity</u> - The beam sensor output signal is <u>not</u> sensitive to the direction of particle beam flight, i.e., the same signal quantity is registered for the same axial beam path regardless of the direction made by the beam thru the pickup, all other factors remaining the same.

b) Intensity Sensitivity (Mutual Impedance) - the beam sensor has an intensity sensitivity (peak voltage developed by electrode and attached networks across 50 ohms, divided by the peak beam current threading thru the axis of the sensor) of 1.25 $\frac{mV}{ma}$ minimum.

c) Displacement Sensitivity - The beam sensor has a displacement sensitivity,

$$20 \operatorname{Log}_{10} \left\{ \text{Plate 1 Voltage} \Big/ \text{Plate 2 Voltage} \right\}$$

divided by the off axis displacement, of 0.77 dB/mm, minimum. This sensitivity applies at each of the two outputs ports of the pickup at a pulse repetition rate of 53 MHz, and with 50 ohm nominal resistive terminators applied to the output ports as loading impedances.

Temperature Range - The beam sensor operates over the temperature range from 4° to 350° Kelvin without damage or electrical derating.

X-ray - 3 megarad total dose.

2. RF Cable System

The signals produced by the beam sensor in the Doubler single beam operation and which are to be transmitted to the multiplexers via the cables are groups of 84 doublet-like pulses. These doublets have a fundamental Fourier component at 53 MHz together with a broad harmonic distribution above this frequency. The doublet groups are amplitude modulated by beam dynamical parameters as well as by an amplitude modulation envelope having about a 1.6 μsec on-time and 60 ns off-time. This envelope is either repetitive, or may be arranged in an arbitrary pattern having from 1 to 13 pulses, depending on the number of booster batches injected.

For a low intensity mode designed for tuning the doubler the on-time may be reduced to about .6 μsec or about 30 doublets to minimize the circulating charge and provide for tuning and special diagnostics. It is necessary that the cable system preserve the amplitude of the doublets within the modulation, on-time envelope to about ±.25 dB. This is so that pairs of sensor signals can be processed for "difference" data which contains the desired measurement of beam displacement.

In order to permit several processing signal options, it is also important to provide broadband low dispersion capability in the cable system and to match paired cables to within about ±2 electrical deg. at 53 MHz. This measure will permit inter-batch trigger development when required, fractional batch processing of sensor data, and capability to scope raw data for test and check purposes without ambiguity.

As electrical stability factors (impedances, loss rates, insertion phase etc.) and low noise, and low dispersion are important aspects of the system cables, cables with core sizes less than .200 inch diameter, and with light braid and questionable jackets are excluded from consideration because of poor stability. With the above factors taken into account, a minimal cable system for the doubler is summarized below:

1) Each of 6 sectors, A thru F, of the doubler accelerator contains terminals for the position detector cables. Each sector is to have 4 specific locations (Service Buildings) to house the terminals. A terminal is defined as a single bay rack and base. See Fermilab drawing 0404-ME-15975 for building location.

2) Each terminal location provides capability to process a total of 12 channels configured as follows:

Channel	Use
0 thru 9	Position data
10	Spare
11	Test

3) The location of the terminal is arranged so that cable path losses do not exceed 10 dB at 50 MHz anone-way path lengths do not exceed 800 ft. These factors wi reduce costs of signal processing equipment and permit standlength spools, rather than special high cost spools, to be usedThe 800 foot value includes a 106 ft. allowance for therun between service building and tunnel.

4) The terminal points are arranged as follows for each sector:

Service Building Terminal	Quad/Sensors Processed by Building Units
A-1	1st 10 sensors C.W. from A-0 reference, see Fermilab dwg. 0404-ME-14491, top right for A-0 reference. No's All thru A-19.
A-2	Next 9 sensors C.W. from above, A21 thru A29.
A-3	Next 8 sensors C.W. from above, A32 thru 39.
A-4	Last 9 sensors in sector, A42 thru A49.
B-1 etc.	pattern as above, 10 CH. MAX/TERM

With this pattern the maximum one-way run will be about 691 feet, with cable losses approaching 10 dB.

5) The cable runs are to be fabricated with RF 213/U, 50Ω, stock cable; 1.3 dB loss/100 ft., .300" core size, heavy braid and noncontaminating heavy jacket or if cost factor permit 3/8" jacketed heliax cable with .63 dB/100 ft loss at 50 MHz.

6) The cable-end connectors are AMP type 225661-2 with gold plated crimp pin. The crimper for this connector is AMP No. 220015-1.

7) The cables are terminated on an insulated G-10 board assembly immediately above the electronics rack assembly, and thereafter fanned out to the input ports of processing units via cables having AMP 1-225661-1 at one end and BNC type at the other.

8) The RG213/U cables are to be designated at each end by 5 digit marker Thomas + Betts (1150-1705), having the following code format:

Sector	Letter A thru F
Quad	number 11 thru 49, C.W. from zero reference in each sector just as in main ring.
Plane of Measurement	V = vertical
	R = radial
Specific Plate	I = inner, 0 = outer
	T = top
	B = bottom

Example: The designation for the second D quad at building A-2, radial plane, inner plate is:

A 23 RI, see

Fermilab drawing 0404-ME-15975 for quad designations.

3. RF Multiplexer

The rf multiplexer for the Doubler is essentially a computer controlled DP12T rf switch. The switch is composed of a grouping of matched series and shunt diodes arranged with interconnected logic decoders and diode drivers. The paths thru the switch are selected by a 4-bit computer control word which is derived on the basis of a data gathering program with proposed software similar to that currently used in the main ring. The channel designations for this program are transmitted to appropriate multiplexers via the Doubler instrumentation network. Since beam data must be derived by differenciating the information which flows thru pairs of switches, the switch paths must be amplitude and phase balanced, channel-for-channel, so that switch error will be small compared to the magnitude of the smallest true quantity, ±.5 dB measured. In addition, the rf paths thru the switches must be as noise-free as possible, the impedance match must be good, crosstalk low, on-to-off ratio high, dynamic range very large, and inserting loss and phase very low. Together with these general properties, the multiplexer must contain provisions for front panel manual operation for diagnostic work, and contain a suitable rf test reference source so that it and associated electronic modules can be easily checked via the main control room.

The rf multiplexers will be located in the service buildings. The environment in these buildings, especially the temperature require That the multiple components be MIL specification wherever possible. Finally, as much commonality as possible must be achieved with existing main accelerator devices so that the proposed device may substitute for main ring service if necessary.

The following tabulation contains the general specifications for the major parameters of the rf multiplexer:

Type	Computer Cont W/Local Remote Provisions
Package	5/W NIM
Test Osc	53 MH ΔdB = 5 dB in Ch. 11
Cable Test	Front Panel Terminal
Switch Type (2/MUX)	SP12T, Electronically Programmable.
Frequency Range	36-70 MHz min.
Input rf Level	+10 dBM nominal, linear
No Damage Level	To +20 dBM max.
Load Impedance	50 ohms nominal
Input Impedance "on", Channel Load Attached	50 ohms nominal
Input VSWR on Channel Load Attached	1.15 max.
Insertion Loss	1.15 dB max
On-to-Off Ratio	Active position to non active position, 60 dB min.

Isolation	Any Unused Channel to common 60 dB
Switching Speed + Transient Feed thru	2 μsec. -80 dBM after 5 μsec.
Channel to Channel Amplitude Balance (2 switches, same throw No.) Among Individual Switches; over Dynamic Range	±.2 dB
Channel to Channel Phase Difference (2 switches same throw No.) at 53 MHz, OVER DYNAMIC RANGE.	<±2 DEG., at 53 MHz
Dynamic Range	70 dB, ref. +10 mW.
Control	4 Bit Parallel binary; 4 load TTL max
Operating; Storage Temperature	-10° + 70°; - 30° + 70°C
Connectors	RF = BNC; Control = Cannon Dem 9 Series
Drivers, decoders	Mil Spec, 54, 55 Series

See Fig. 3, Fermilab dwg. EE-103320 for schematic details.

4. <u>Service Building Electronics</u>

The signals which are developed by the beamline detectors and which are transmitted to the MUX must be processed to match the data channel format requirements. The initial processing will take place within a designated electronics rack located in each of 24 service buildings. The processign equipment contained in the rack consists of four principal modules (1) beam position unit, (2) beam trigger unit, (3) signal processor and digital interface, and (4) power group. These devices will collectively produce a normalized Vertical or Radial position value, interface the signal quantities with the dataway, control the various modes, and provide for diagnostic capability.

For the special Doubler Beam Mode, FRACTIONAL BATCH SINGLE TURN, (FBST), special tuning operations can be accomplished during injection. In this mode, the first passage of beam by all designated detectors will be read and stored. Following a number of cycles, say 11, the data can be displayed and tuning procedures initiated. The role of the equipment in the service building orbit electronics rack is to process and connect the two beam-derived rf MUX signals "A" out and "B" out, into signals which match the data channel and to control the operation of the various data-gathering devices used in the orbit system. Figure 4 contains the general outline of the modules and the interconnections between system modules.

In the "each house" part of this figure, the MADC, CAMAC and HLU are not considered part of the data developing system, but rather the data-gathering system.

Two operational modes are console selectable, NORMAL, and FRACTIONAL BATCH SINGLE TURN; a diagnostic mode. When the NORMAL mode is selected, the data chosen for display can be CLOSED ORBIT, FAST TIME PLOT, DETECTOR TEST, or 1ST TURN BEAM. When CLOSED ORBIT is requested, the RF MUX in each house is sequenced under computer control thru each of 11 channels (CH 0-to-10). Normalized position information is obtained on each MUX channel and transmitted via SIGNAL PROCESSOR + DIGITAL INTERFACE to the MADC and thereafter via the data channel to the 530 computer and TEK 611 display. The position values derived in this process are timed to a particular part of the Doubler Cycle by the interrupt and by the timing data contained within the MAC buffer, i.e., data readback can be timed to a particular part of the machine's cycle. A 40 ms time window is required for all necessary data collection.

Orbit data will be taken on each machine cycle at selectable times. The proposed minimum separation between data collection operations is 50 min, while timing precision proposed for these data is ±10 ms.

For FAST TIME PLOTTING, the RF MUX is driven via the DO channel select lines to a specific channel. Position data for that channel will appear at the input to the MADC. Data readback at regular intervals, initiated by the 300 Hz interrupt into the MAC, will establish a display with discrete position values versus "time into Doubler Cycle" on the TEK 611 unit.

For the DETECTOR TEST operation, the DO Channel Select lines will select channel 11. This channel contains an internal test oscillator which simulates a beam detector signal having a fixed position error of 5 dB (=6.5 mm) i.e., the "A" Out signal is almost twice the "B" Out signal. If the Beam Position Unit and the Signal Processor and Digital Interface unit are functioning normally, the MADC receives a constant-level signal which is displayed as a vertical line on the TEK 611 unit, 24 such lines indicate normal performance, while the absence of line or a line of nonstandard height indicates equipment trouble. All of the above functional conditions, CLOSED ORBIT, FAST TIME PLOT, DET TEST, are derived from the Beam Position output signal and since they have position as a common coordinate, each can be switched to one data channel of the MADC.

For the 1ST TURN BEAM, data is derived from a different source and requires a separate data channel. In this case, the data is derived via a BEAM TRIGGER RCVR. This device is sensitive to the rf amplitude level of the beam signal and produces a TTL logic "1" when beam is present, and logic "0" when the beam is absent. 1ST TURN BEAM data is derived by cycling the RF MUX via the DO channel select lines and plotting the existence of the logic signals at the MADC input. 1ST TURN BEAM is a relatively complex routine and requires the following sequence of operations for complete data gathering. First, one machine batch (84 bunches) is selected for injection so as to minimize x-ray radiation in the event the beam intercepts the walls of the vacuum line and in addition, the CONSOLE inputs a request for 1ST TURN BEAM operation. A selectable interrupt residing within a machine cycle time locks out data collection during this cycle, but permits data collection on the next machine cycle. A specific MUX channel is also selected prior to each machine cycle. Next, a timing pulse DOUBLER INJ, Fig. 4, set just prior to injection, requests the MADC to obtain BEAM TRIGGER data and advances a cycle counter so that as many as 10 data collection intervals, one for each machine cycle, can be accomplished. The channel selection (one selection in each Service Building), and the DOUBLER INJ pulse, both coming prior to injection, set up the necessary conditions for observation of the injected beam by the detectors. Lastly, the beam is sensed by the BEAM TRIGGER RCVR, the SIGNAL PROCESSOR and DIGITAL INTERFACE unit latches the data (for 50 ms minimum) and 24 discrete values, one from each service building, are collected and plotted. At the end of the pre-selected number of cycles, all data is available and can be displayed. Work related to magnet quenching thresholds currently underway may modify or exclude this mode if very low thresholds are encountered.

For the FRACTIONAL BATCH SINGLE TURN mode data is collected as in the 1ST TURN BEAM function described above, but the position information on the batch is peak detected, held , and thereafter outputted for display. The data plotted in the FRACTIONAL BATCH SINGLE TURN mode will be useful in establishing control parameters for optimum closed orbits. Ten or more Doubler cycles will be necessary to obtain all data needed for single complete turn information.

In the discussion above and in the section below, both operational modes and functions of these modes are accomplished using common electronic modules rather than separate modules for each. In this way sizable savings in hardware and expenditures can be made.

The operating control program structure will be similar to, but not necessarily a copy of the existing program; PAGE 12, for the 530 and BMP-NEW for the MAC routine. Additions and modifications to these routines would be required to (1) select and implement the FRACTIONAL BATCH SINGLE TURN mode (2) time the channel selections to a point in the Doubler cycle prior to injection (3) transmit the various status and mode commands to the SIGNAL PROCESSOR + DIGITAL INTERFACE, (4) arrange the data and scale parameters in correct format for the TEK 611 CRT display, (5) select 2 sample time for CLOSED ORBIT data gathering and (6) restructure timing and mode controls to correspond to the Doubler's master timing structure.

<u>Beam Position Detector Summary</u>

The Position Detector will consist of electronic devices configured as in Fig. 5. The Postion Detector functions by converting the amplitude ratio of the two input signals, BEAM "A" and BEAM "B", into phase differences which appear at ports "C" and "D", Fig. 5. A passive processor is used to make this conversion. The processor consists of an interconnected group of rf splitters, quadrature hybrids, and phase cables as shown in Fig. 5. The Phase transfer function from inputs at Beam "A" and Beam "B" relative to points C and D is

$$\Delta\ /_{C/D} = 6.3°/_{db\Delta A/B} = 4.85°/mm$$

The amplitude modulations which result from changes in intensity and changes in input ratio are removed by a dual channel constant phase limiter. The limiter consists of two separate seven-stage transistor amplifier/limiters arranged in a linear array of semiconductors and attached to a groundplane within the NIM module. Thruput delays are minimized by this arrangement, and the seven stages will produce limiting over at least a 60 dB dynamic input range. The -3 dB bandwidth of the limiter is 20 MHz minimum. Microwave transistors are used in the construction of the limiter to reduce the overall phase variations with rf drive level. The output voltages, referred to 50 ohms, will be a minimum of 1.5V P-P at 53 MHz, a value sufficient to drive the doubly-balanced mixer detector to full output, i.e., 0.25V Peak for Δ = 90° = 18.5 mm.

The low-pass-filter, LPF, is used in the input section to secure a minimum of 30 dB attenuation for the machine's second harmonic 106 MHz.

Post detector processing consists of scaling and buffering the LPF output to match it to the data input of the SIGNAL PROCESSOR + DIGITAL INTERFACE unit. Scaling and buffering will be achieved using standard operational amplifiers and power follower modules. The output scale factor will be set by adjusting the gain of the last stage for 0.5V/mm displacement.

Circuit-point dc regulators will be used to supply critical dc voltages. The final amplifiers in the Position Detector will be provided with an INHIBIT circuit to allow control of the output during dead time and for local zeroing operations.

Beam Trigger Receiver Summary

The Beam Trigger Receiver is shown in Fig. 6. This device is designed to produce a TTL logic "1" output for "beam present" conditions while a TTL logic "0" otherwise. The dynamic range of the receiver is greater than 60 dB, i.e., >1,000:1. This range is achieved by a fire section rf/limiter with AGC and an amplitude detector followed by a level shift amplifier and gate. Missing beam bunches will be observable when 3 or more consecutive bunches are missed, i.e., when a 60 ns or larger hole appears in the bunch.

Unfiltered beam samples, doublets, are obtained from tap-off points within the Postion Detector and connect directly to each of the "A" and "B" inputs. More than 60 dB of gain at 53 MHz is distributed about evenly between stages of limiter/amplifier and the detector driver amplifier. The rf signal developed by the detector driver is AM detected in a full wave circuit, filtered, and applied to the fast comparator, NE 521N. The comparator output is adjusted by TRIG LEVEL to establish a low probability of false-alarms due to residual noise peaks and to secure the overall dynamic properties needed for signal identification. A standard TTL type driven gate is used to buffer the output from the load. Test ports will permit use of the Beam Trigger output for test and diagnostic purposes. See Fermilab dwg. EE-103311, Fig. 6, for schematic details.

Signal Processor and Digital Interface Summary

It is proposed that the Signal Processor and Digital Interface have two basic functions: a) the conditioning and acquisition of the beam position signal and b) the communication and interpretation of the various digital status and control signals needed for operation of the service building electronics.

Signal Processor/Signal Interface

The Signal Processor is shown in Fig. 7. Two analog signal paths are selectable via the analog switch. In the NORMAL mode of operation, the PATH SELECT control line selects the path bypassing the peak detector, sample/hold and lopass filter. In this mode, the beam position information is smoothed with the input lopass filter and is sent on to the MADC for digitizing. The input impedance of the input lopass filter is at least 1000Ω.

In the FRACTIONAL BATCH SINGLE TURN mode the path through the peak detector is selected. The peak detector is designed to catch and store the fast position signals that occur in this mode. The input lopass filter guards against the detection of false high-speed noise spikes. The peak detector will have an input range of ±5V and an acquisition time of 150 ns. The peak detector is capable of peak detecting an input signal, holding a detected signal and resetting to zero depending on the status of the PEAK DETECT/$\overline{\text{HOLD}}$ and $\overline{\text{RESET}}$ control signals.

The sample/hold circuit follows the peak detector for long-term storage of signals after peak detection. An 8-bit analog-to-digital and digital-to-analog combination is used to avoid drift and droop problems. This circuit will have an acquisition time of no greater than 100 μsec. The CONVERT and END OF CONVERT signals will control and monitor the status of the sample/hold, respectively. An output lopass filter is added for signal smoothing, and the position signal is then sent on to the MADC. The Digital Interface circuitry, Fig. 8, is designed to coordinate commands from the Doubler Orbit Program with the electronics present in the service building.

The central operator in the Interface is a 1-bit microprocessor, MC14500B, and its supporting hardware.

This processor will be interfaced with the external world with buffers, so that all inputs and outputs will have standard TTL logic levels and drive characteristics. CABLE DATA and BEAM TRIG are signals generated elsewhere in the house electronics, whereas the MODE and STATUS No. 1 signals are developed by the Orbit Program. The remaining inputs are for future use. The MODE input signal will determine whether the Digital Interface functions in the NORMAL or SINGLE BATCH SINGLE TURN mode. The MODE signal must be a constant level; logical 0 for NORMAL mode and logical 1 for SINGLE BATCH SINGLE TURN mode. The STATUS No 1 line is used to transmit to the processor a reset pulse, 5-to-10 μsec in length. This reset pulse will clear all output lines and registers and return the processor to the first step in its program.

In the NORMAL mode the PATH SELECT control line is set so as to select the path for NORMAL operation, and data is acquired by above outlined methods. CABLE DATA will be transferred to the CABLE QUALITY output line, while the peak detector, sample/hold and 1st TURN BEAM output will be disabled. Whenever a change in MODE control signal is generated by the Doubler Orbit Program, a reset pulse will also be generated to follow it, making the Interface ready for proper data collection. Both the MODE and reset (STATUS No. 1) signals must be valid and complete at least 1 msec prior to the beginning of the doubler cycle. In summary, a logical 0 on the MODE line with its ensuing initial reset pulse will allow the following data gathering functions to be performed: CLOSED ORBIT, DETECTOR TEST and FAST TIME PLOT.

When the MODE signal is at a logical 1, the following functions are enabled: FRACTIONAL BATCH SINGLE TURN and 1st TURN BEAM. In this mode, a reset pulse is required not only with every change in the MODE line, but also preceding each and every doubler cycle. Again, the MODE and reset signals must be valid and complete no less than 1 msec before the doubler cycle.

When the FRACTIONAL BATCH SINGLE TURN mode is chosen, the signal path through the peak detector and sample/hold is selected. Upon reception of a reset pulse (STATUS No. 1), the peak detector will be reset and enabled and the leading edge of the BEAM TRIG signal will be transferred to and latched at the 1st TURN BEAM output for no less than 50 msec. At the trailing edge of the BEAM TRIG signal, the sample/hold will digitize the beam position signal. Data can then be collected by the MADC. The μP will then await the next reset command which will initiate the process again.

Status of Monitor System

To date one sector (1/6) of the Doubler has been cabled and one rack of equipment has been installed to support sector testing. Prototype units of the rf multiplexer, Position unit, Beam trigger unit and Data interface have been constructed and each meets its general requirements. Early models of the beam pickup have also been manufactured and these devices meet requirements. Final versions of the beam pickup are currently undergoing electrical, mechanical, and cold testing. Beam derived information during early mini sector testing with low level beams has demonstrated overall system feasibility.

PART II - DUAL BEAM ORBIT MONITORING

To obtain orbit data on individual beams when both are present in the beamline requires the use of a beam detector with directional properties or the use of other techniques and/or devices to separate individual beam information. Some detectors, can be made sensitive to beam direction, examples are the strip-transmission-line detector and the terminated-loop detector, both being versions of the general class of rf directional couplers. The measure of the directivity for directional beam detectors is related to the voltage sensitivity at a designated output signal port when equivalent beams are made to thread the detector first in one direction then in the opposite direction. The ratio of the quantities gives the directivity thus.

$$S_d = \frac{V_f}{V_r} \Bigg|_{q \text{ fwd} = q \text{ reverse.}}$$

and where V_f, V_r = forward and reverse voltages developed for the same beam traveling in the forward then in the reverse directions.

When $S_d = 1$ the detector is nondirectional, when $S_d >> 1$, say 100, the detector is very directional. V_r is an error developing quantity when the detector is used in a dual beam configuration because it is an additive spurious signal with the desired signal produced by the forward going beam. The estimated directivity for a "cost effective" detector is only in the range of 26-30 dB. This means that the spurious level at each of the measurement ports is 1/20 to 1/30th of the main quantity to be measured.

For the condition that both p and $\bar{p}$ bunch intensities are equal within a factor of the lack of perfect directivity ($S_d \to \infty$) would not preclude useful orbit determinations, but some error would be present in the processed quantities. For example, if both p and $\bar{p}$ beams were centralized, say within a few mm of ℄, had equal intensities, and a 26 dB detector directivity factor was achieved, the spruious error component in the desired signal would be 1/20 x 100% = 5%, while possible phase errors would reach $\tan^{-1} \frac{.05}{1.0} = \pm 2.9°$. However, if the $\bar{p}$ beam were smaller by 10 dB the amplitude error would increase to 15% and phase error to ±9.5°. For beams off axis, the ratio of the desired to spurious signal at the detectors output port can change giving rise to more error in the resultant orbit data. It is desirable therefore to establish directivity at a factor of 100 as an eventual goal. It is important to also point out that a total error could only be arrived at after the kind of processing electronics is established. In the case of a SUM and DIFFERENCE processor both the amplitude and phase error due to the detector would give rise to error. For the AM-to-PM conversion and peak detector Superdamper processor, only the amplitude errors, to first order, are relevant. It is important therefore that the choice of detector and its attached processor be analyzed prior to judging overall errors.

Allowing for operational conditions (spilling, tuning, etc.) which would permit the proton beam to be initially adjusted for intensity correspondence whith the $\bar{p}$ beam, the traveling wave beam detector could be useful for dual beam orbit acquisition. Sufficient space in the quadrupole magnet assembly/spool, of course, would have to be made for the device, and the necessary connection and adaptive devices.

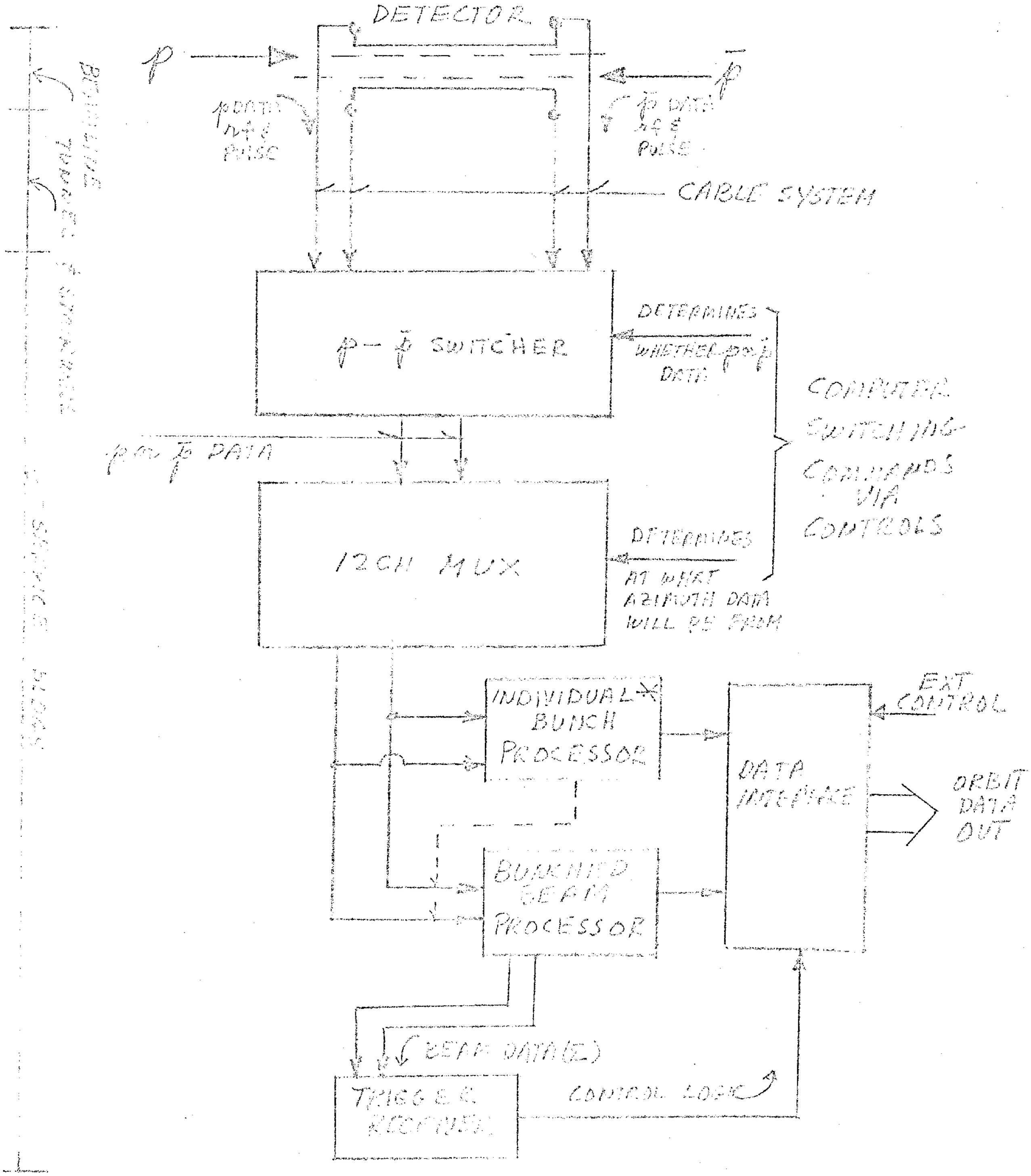
The following table lists three accelerator modes wherein such a directional detector could be used.

ORBIT DATA COLLECTION, DUAL BEAMS

MODE	CONDITIONS
1. Proton beam tuneup, fraction of single batch, very low intensity, 5×10^7 p/b for 30 bunches, bunched at 53.1 MHz.	Low intensity via damper kick-out, spilling, detuning, etc.,one set of detector voltages processed via sensitive bunched-beam processor as in part 1.
2. Single beam high intensity, approaching 1×10^{14} p. total, high duty cycle, 1×10^3 bunches, bunched at 53 MHz.	One set of detector signals processed, switched attenuators to reduce peak beam signal level, processing via bunched beams processor per part 1.
3. Dual beams, $p,\bar{p}$, intensity, 10^9-to-10^{10} p/b, low duty factor (1-to-20 bunches Only), flight path in opposite directions.	First adjust p beam to equal $\bar{p}$ beam, switch to damper type processor, multiplex between p and $\bar{p}$ beam quantities with individual pulses to get orbits. Set p beam to high intensity for physics following orbit determinations.

A block diagram of a system using a directional detector is shown below, while the characteristics of one possible detector are contained in Appendix II.

EXAMPLE OF A DUAL BEAM PROCESSING CHAIN



* THIS DEVICE CAN BE SUPERDAMPED TYPE OR SHOCK-EXCITED RINGING ... OR ATTACHED TO BUNCHED BEAM PROCESSOR

EDH 1/7/79

APPENDIX I

Beam Detector Parameters (nondirectional)

A. Design Bunch

1.	Max Electrical Width	4 ns
2.	Max Protons/bunch	1×10^{11} running
3.	Min Protons/bunch	5×10^{7} pilot beam

B. Bunch PRF

1.	Tuneup pilot	30 bunches at 53 MHz
2.	Running high intensity	53 MHz; ∿1000 bunches

C. Detector

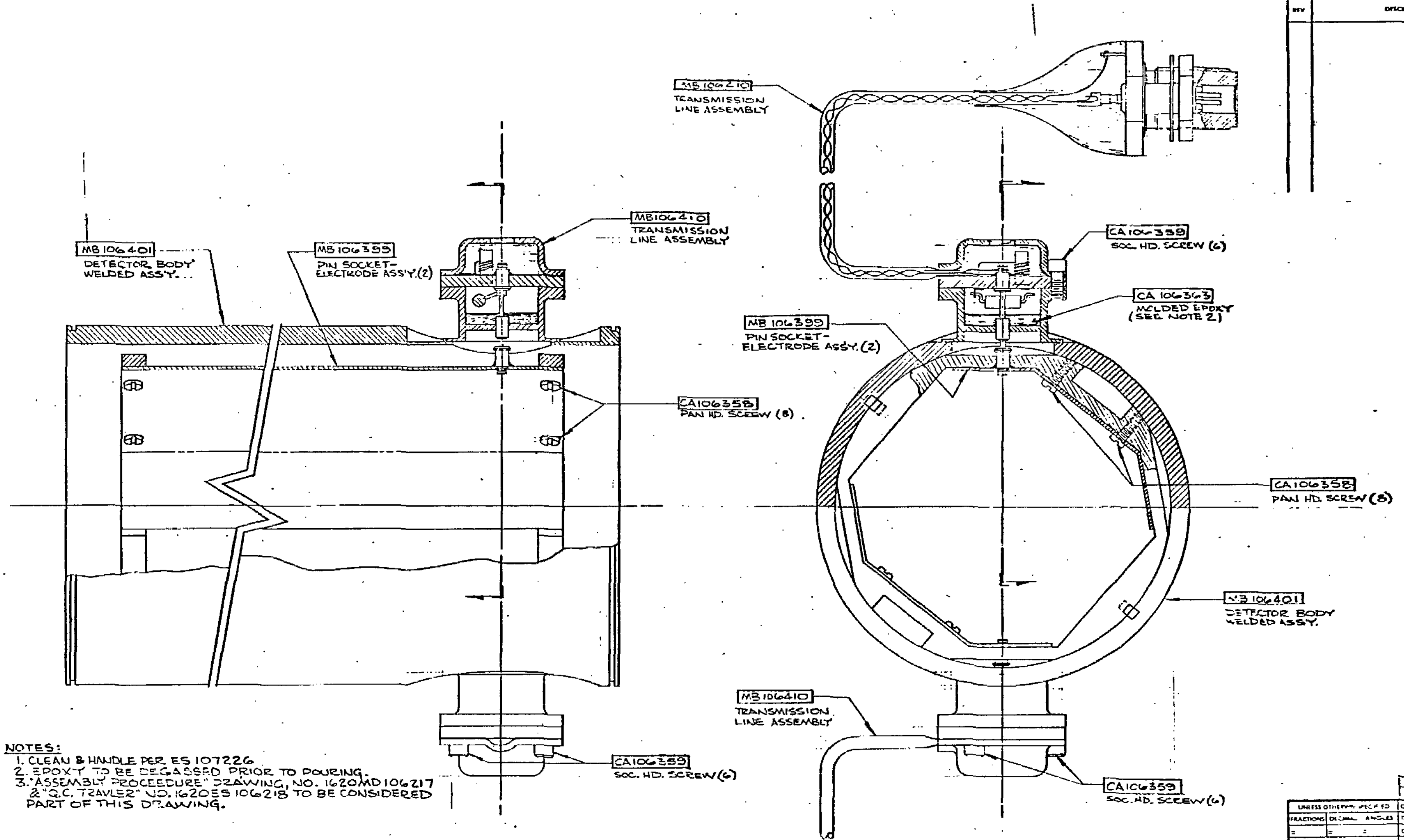
1.	Type	parallel plate, electrostatic
2.	Body Length	15.2 cm
3.	Plate Length	12.7 cm
4.	Diameter	7.6 cm
5.	Aperture	6.35 cm
6.	Electrode Capacity	28 pf
7.	Directional Sensitivity	1, i.e., nondirectional
8.	Intensity Sensitivity	1.25 ohms
9.	Displacement Sensitivity	10% diff/mm
10.	Coupler Type wire twistline	
11.	Coupler Heat Loss	< .05 watts
12.	Driving Impedance	50Ω nominal
13.	Frequency Range (4ns/pulse)	dc - 100 MHz
14.	Number measurement planes/unit	1
15.	VSWR	<1.1:1, to 106 MHz
16.	Radiation Resistance	3 Mrad total dose
17.	Beam Induced Heat Load (damping R)	.2 watts max at 10^{14}p. total
18.	Dual Beam Capability	no
19.	Cost	$800 per det. est.
20.	Dual Plane Capability	yes, for 2 x length

APPENDIX II

Beam Detector Parameters (directional)

A.	Design Bunch	
1.	Electrical Width	4 ns single beam 3 ns dual beam
2.	Max Protons	1×10^{11}/bunch-running
3.	Min Protons	5×10^{7}/bunch-pilot
4.	Max $\bar{p}$	1×10^{10}/bunch-running
5.	Min $\bar{p}$	1×10^{8}/bunch-run-orbit
B.	Bunch PRF	
1.	Tuneup pilot	30 bunches at 53 MHz once per cycle
2.	Running single beam	53 MHz
3.	Dual beam, p, $\bar{p}$	47 KHz - 1 MHz
C.	Detector	
1.	Type	directional detector/short strip
2.	Length overall	51 cm, (20 in)
3.	Shape of detector Cross-section	square, rounded corner 10 cm. side
4.	Aperture	6 cm est.
5.	Strip impedance	50 ohms
6.	Coupling structure	coaxial cable, semirigid
7.	Directional sensitivity	>20
8.	Intensity sensitivity	2.5 ohms min.
9.	Displacement sensitivity	15% diff/mm minimum
10.	Coupler thermal loss	<.15 watts
11.	Driving Impedance	50Ω
12.	Pulse width range	.5-4 ns nominal
13.	Number of measurement planes	1
14.	Beam induced heat load	none
15.	Dual plane capability	TBD
16.	VSWR	<1.07:1 to 400 MHz
17.	Radiation Resistance	3 Mrad total dose
18.	Cost	$1,200 est.

*By careful design and fabrication, but with added cost this value may approach a factor of 100.



NOTES:
1. CLEAN & HANDLE PER ES 107226
2. EPOXY TO BE DEGASSED PRIOR TO POURING.
3. "ASSEMBLY PROCEEDURE" DRAWING, NO. 1620MD106217 & "Q.C. TRAVLER" NO. 1620ES106218 TO BE CONSIDERED PART OF THIS DRAWING.

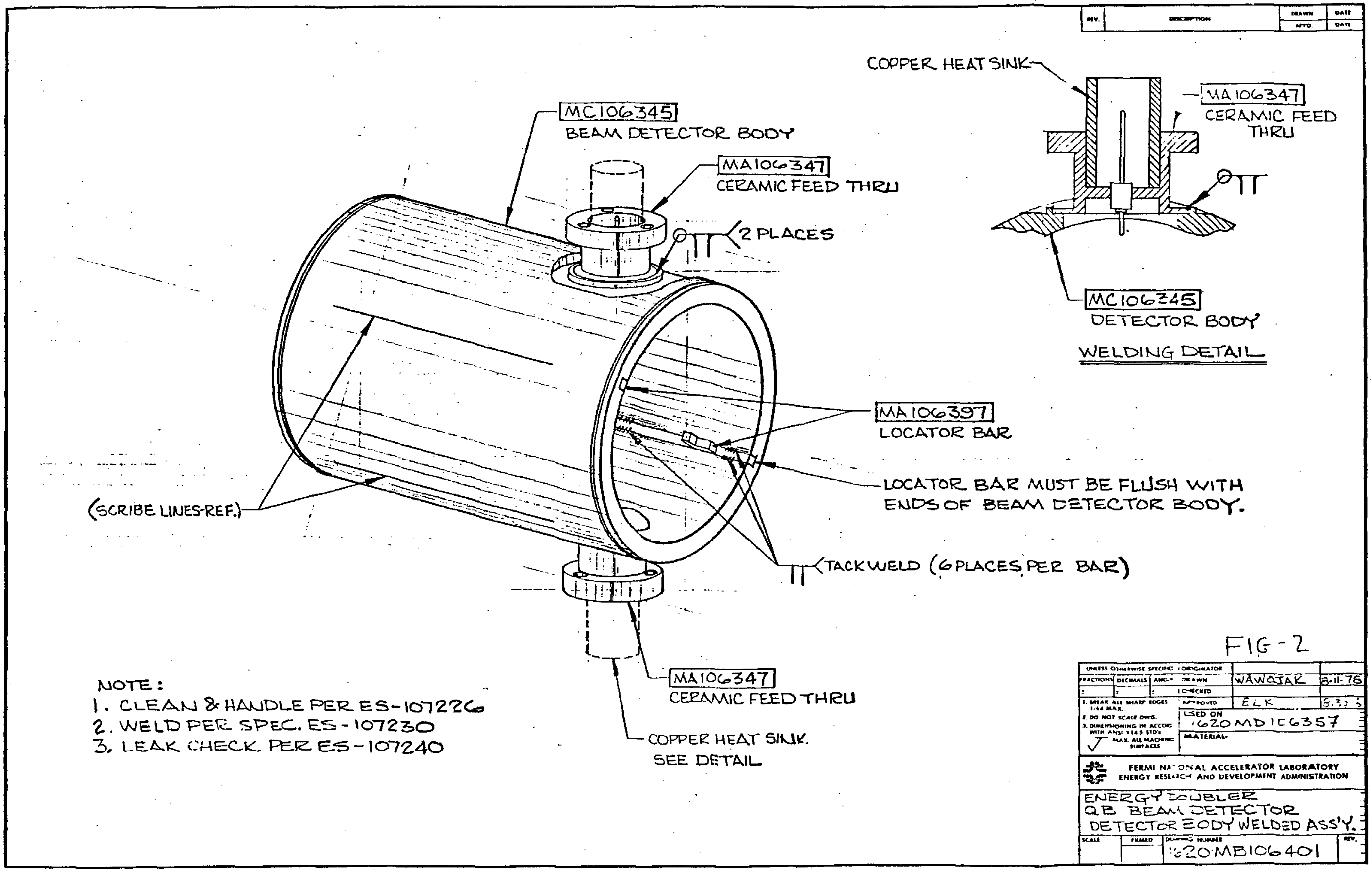
FIG-1

UNLESS OTHERWISE SPECIFIED	ORIGINATOR
FRACTIONS DECIMAL ANGLES	DRAWN NAWOJAK 3-18-78
	CHECKED
1. BREAK ALL SHARP EDGES 1/64 MAX. 2. DO NOT SCALE DWG 3. DIMENSIONING & ACCORD WITH ANSI Y14 ... MAX. ALL MACHINED SURFACES	APPROVED E.L.K. 5-30-8
	USED ON
	MATERIAL -

FERMI NATIONAL ACCELERATOR LABORATORY
U.S. DEPARTMENT OF ENERGY

ENERGY DOUBLER
QB BEAM DETECTOR ASSEMBLY

SCALE | FLAG | DRAWING NUMBER 1620 MD 106357 | REV.


MC106345
BEAM DETECTOR BODY
MA106347
CERAMIC FEED THRU
2 PLACES
COPPER HEAT SINK
MA106347
CERAMIC FEED THRU
MC106345
DETECTOR BODY
WELDING DETAIL
MA106397
LOCATOR BAR
LOCATOR BAR MUST BE FLUSH WITH ENDS OF BEAM DETECTOR BODY.
TACK WELD (6 PLACES PER BAR)
(SCRIBE LINES-REF.)
MA106347
CERAMIC FEED THRU
COPPER HEAT SINK. SEE DETAIL
NOTE:
1. CLEAN & HANDLE PER ES-107226
2. WELD PER SPEC. ES-107230
3. LEAK CHECK PER ES-107240
REV. DESCRIPTION DRAWN DATE APPD. DATE
UNLESS OTHERWISE SPECIFIC
FRACTIONS DECIMALS ANGLE
ORIGINATOR
DRAWN WAWAJAR 8-11-76
CHECKED
APPROVED ELK
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 1620MD106357
MATERIAL
FERMI NATIONAL ACCELERATOR LABORATORY
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
ENERGY DOUBLER
QB BEAM DETECTOR
DETECTOR BODY WELDED ASS'Y.
SCALE
FILMED
DRAWING NUMBER 1620-MB106401
REV.
FIG-2

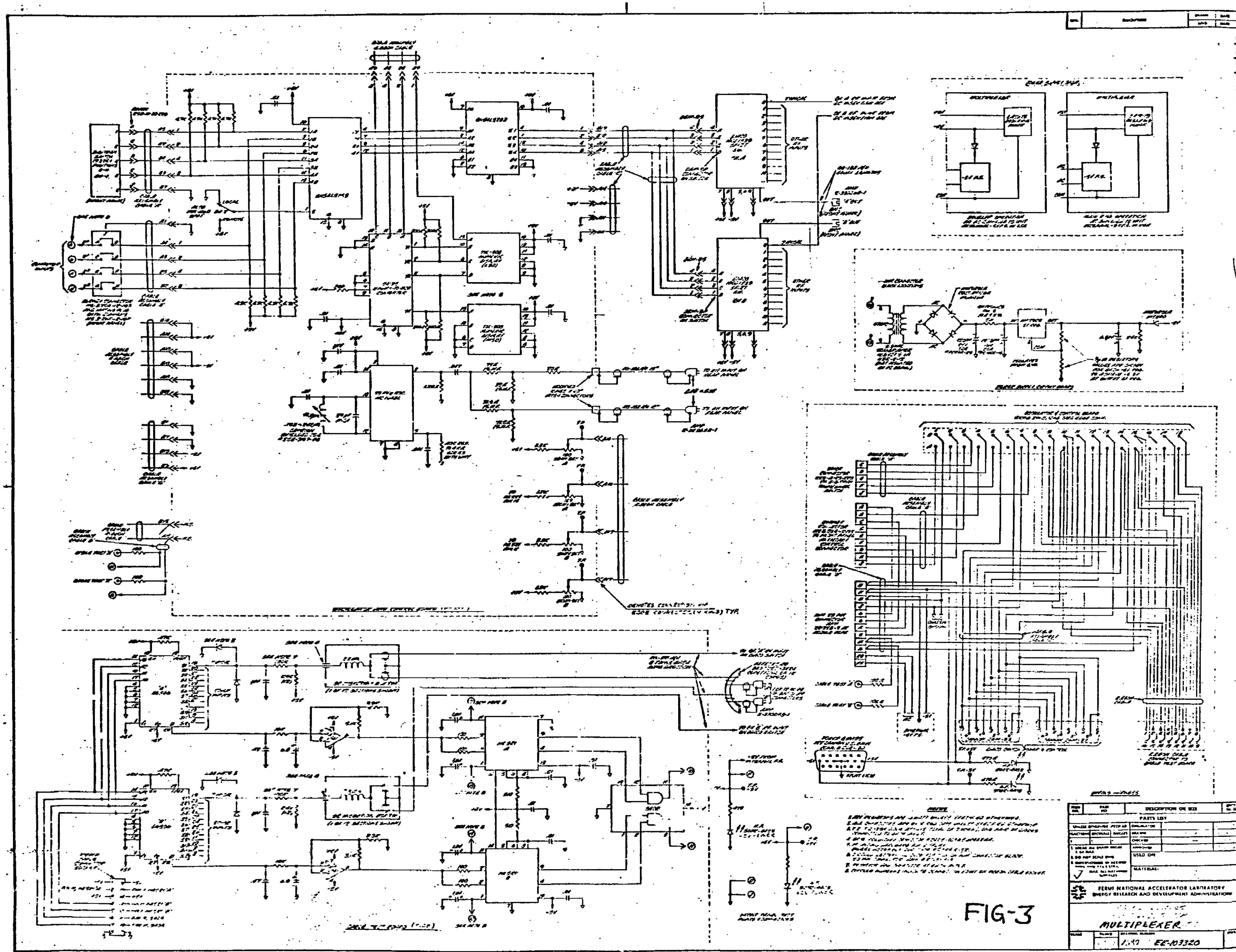

FERMI NATIONAL ACCELERATOR LABORATORY
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
MULTIPLEXER
EE-103320

FIG-3

FERMILAB ENGINEERING NOTE

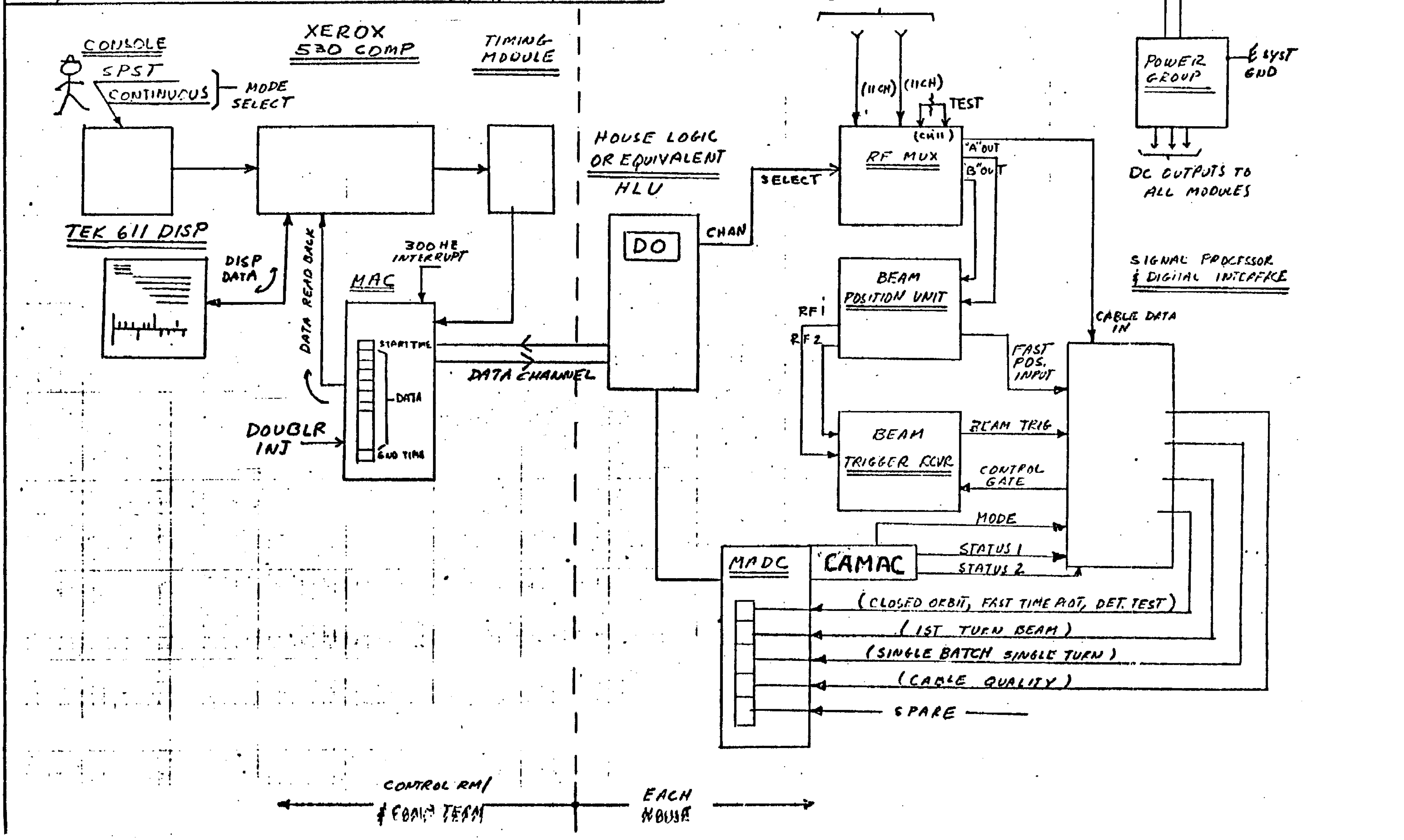
SECTION	PROJECT	SERIAL-CATEGORY	PAGE
E/E	DOUBLER	FIG 4	

SUBJECT: BEAM ORBIT DATA SYSTEM BLOCK DIAGRAM

NAME: E.F. Higgins

DATE: 1/24/78

REVISION DATE:



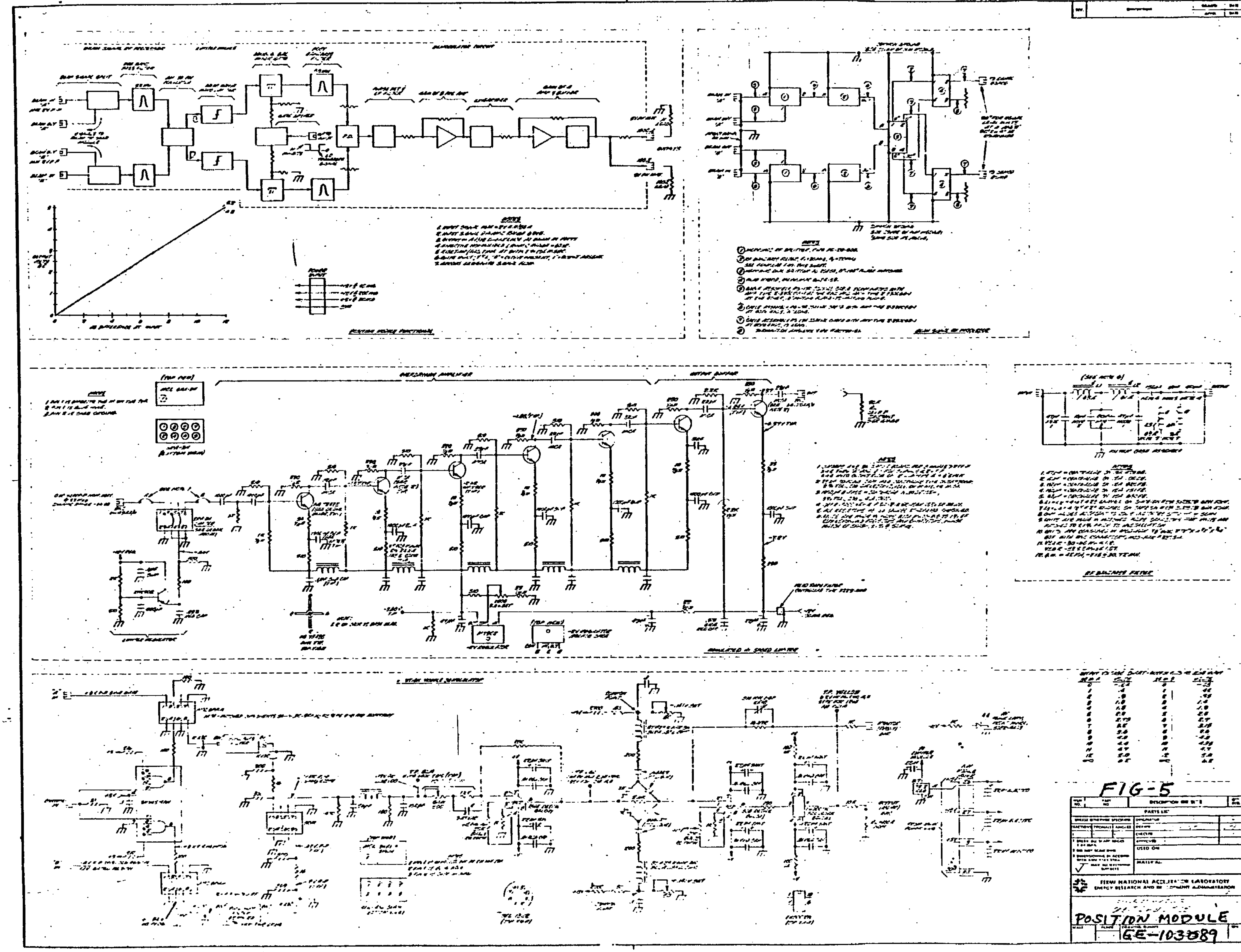

FERMI NATIONAL ACCELERATOR LABORATORY
POSITION MODULE
GE-103089

FIG-5

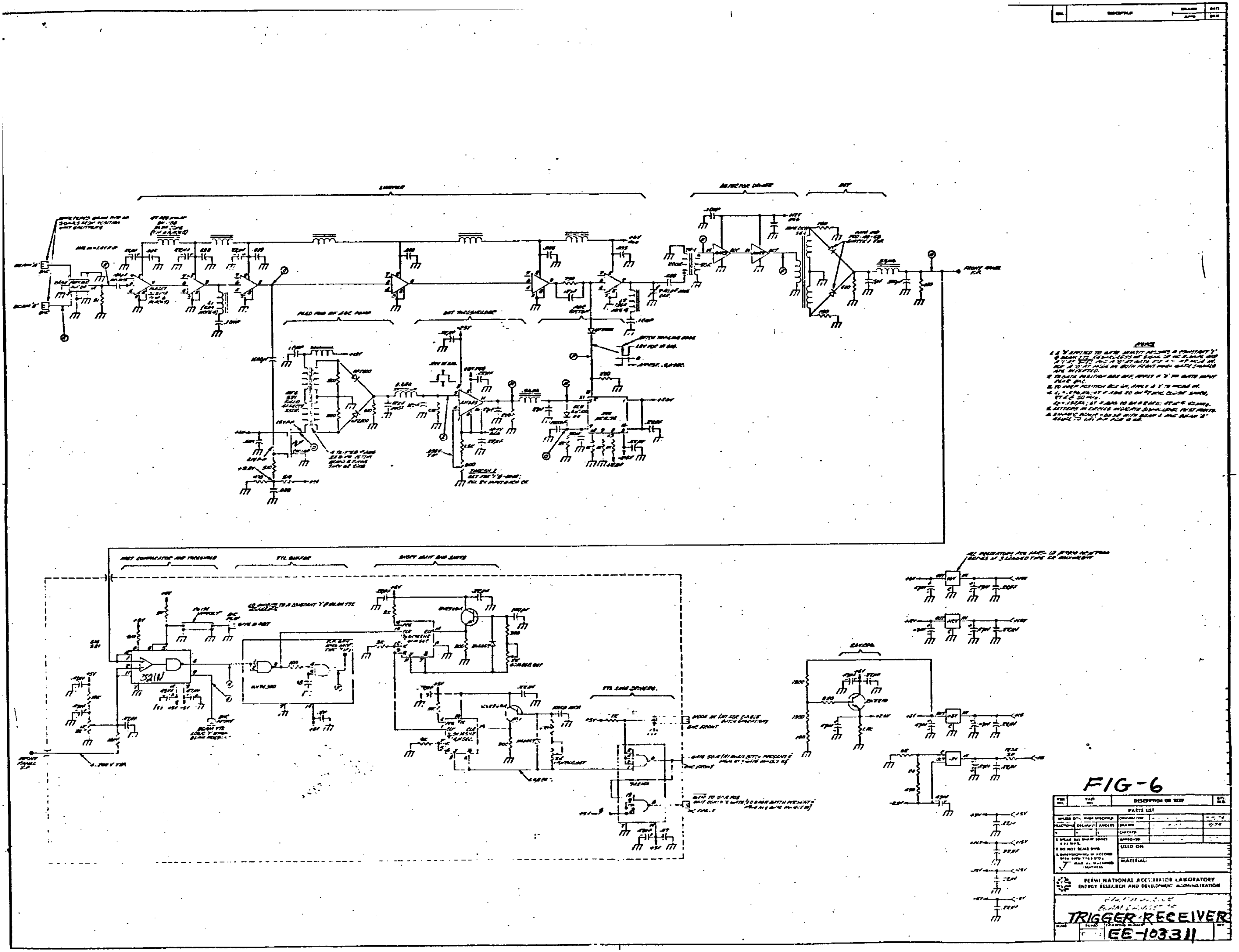

521N
TTL LINE DRIVERS
PARTS LIST
USED ON
MATERIAL
FERMI NATIONAL ACCELERATOR LABORATORY
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
TRIGGER RECEIVER
EE-103311

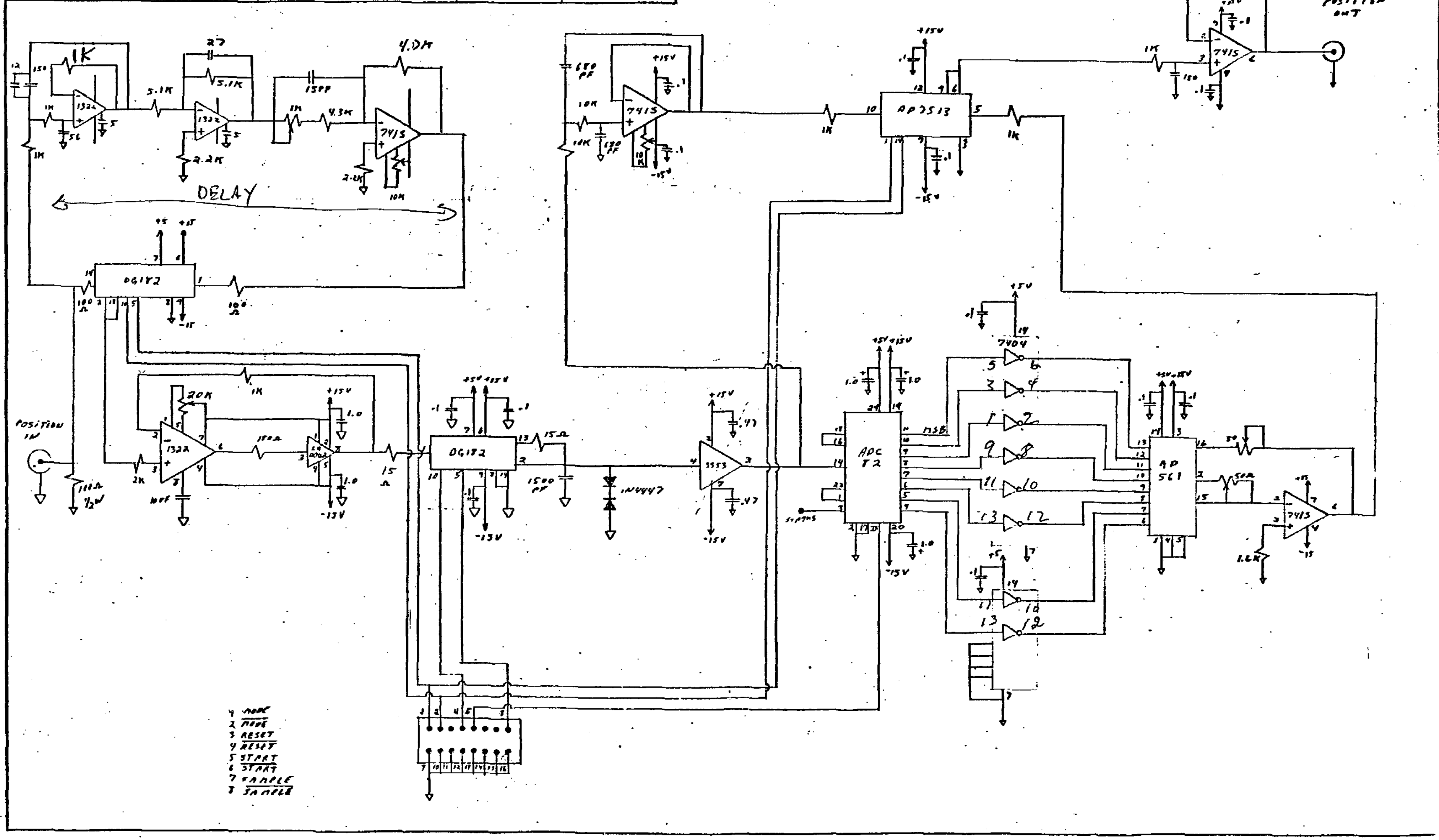
FIG-6

FERMILAB
ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE

SUBJECT: ENERGY DOUBLER SIGNAL PROCESSING UNIT ANALOG BOARD — FIG-7

NAME	
DATE	REVISION DATE



FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE
SUBJECT: ENERGY SIGNAL LOGIC POWDLER PROCESSING BOARD unit FIG - 8	NAME: J.Q.			
	DATE: 7/7/75	REVISION DATE