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BEAM DETECTOR ASSEMBLY FOR THE FERMILAB ENERGY DOUBLER

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ABSTRACT

The testing and production of the Fermilab Energy Doubler has necessitated the development of a detection device to locate a proton beam with an accuracy and repeatability of ± .5 mm relative to the centerline of a 2-7/8" bore tube. This information is essential for focusing and "steering" of the beam around a four mile synchrotron. The detectors are positioned, to measure horizontal and vertical off-axis displacement, alternately at each quadrupole magnet. The severity of the operating environment, as well as stringent electrical parameters, have necessitated the development of a number of design innovations. Both the mechanical and electrical considerations will be discussed as they relate to operational criteria.

I. INTRODUCTION

The Fermilab Energy Doubler accelerator will contain nearly one thousand cryogenically cooled magnet assemblies. The doubler beam will be required to thread a relatively small aperture along its orbital path within these magnets. Knowledge of the orbit in both the vertical and horizontal planes is a natural requirement during normal machine operations as well as during tune-up and diagnostic periods.

An orbit monitoring system for the single beam mode has been devised for the doubler machine which permits the required position data to be determined at any designated time during an acceleration cycle, from injection to extraction. Also, as a measure to circumvent possible beam induced magnet quenches during tune-up, i.e., before an operational orbit has been completely established, the orbit system contains provisions for a special low-intensity mode. In this mode the amount of circulating charge is restricted to a value below the quench threshold through spilling and detuning techniques. With the low intensity "safe beam" acting as a pilot charge, the control settings of machine variables can be obtained via beam detector data and a best orbit established prior to normal, high intensity running. It is currently estimated that the pilot beam will contain a total of roughly 1×10^9 protons in 30 adjacent bunches spaced about 19 apart.

The principal beam sensing element in the orbit system is a cryogenically cooled parallel plate, electrostatic detector having a 12.7 cm electrode length, a 6.3 cm wide aperture, and a low thermal loss rf twistline coupling structure. The twistline couples the detected beam signal from the 4.5°K electrode connection to the 300°K output connector affixed to the exterior of each quadrupole assembly.

The mechanical and electrical design of the detector will be presented in this paper.

II. MECHANICAL DESIGN

The criteria used as bases for the mechanical design of the Energy Doubler beam sensor fall into several distinct categories, each of which will be detailed individually.

These criteria are: accuracy in position detection of a proton beam; mechanical integrity under a wide range of possible operating conditions; packaging, relative not only to assembly of the unit itself, but also to its installation in the machine; and repairability, should damage occur in handling. Naturally, the result of all of the above must be a package to meet the electrical parameters discussed in the following section.

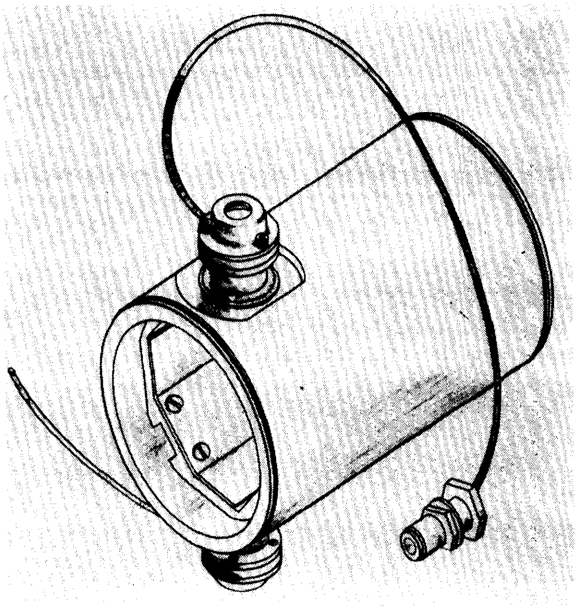

Fig. 1: Beam Detector Assembly

Accuracy

Locating the position of a proton beam with some degree of precision is of fundamental importance. A resolution accuracy of ± .5 mm has been chosen as an acceptable tolerance.

Heavy wall stainless steel tubing houses the detector electrodes. The heavy wall permits boring of the detector I.D., eliminating manufacturing tolerances on the material itself. The electrode plates are attached to two G-10 supports. Again, machining tolerances are held to a minimum. There is, however, a factor here that must be taken into account. Since the Fermilab machine is a superconducting accelerator, the detector must operate at 4.5°K, and must reach that from room temperature without damage. The body of the detector is cooled by conduction from single phase liquid helium. The G-10 supports, on the other hand, are cooled by radiation from the body. For this reason, the two cannot be rigidly fixed, but rather, must be free to expand and contract independently, maintaining a common centerline. The G-10 supports, therefore, are machined .010" undersize on the diameter and secured with two locator bars (see Fig. 3). These bars both position the supports and allow free movement within an acceptable limit to provide the desired accuracy.

The relative location of the body and electrode centerlines are accurate and repeatable to within .25 mm from room temperature to 4.5°K.

Mechanical Integrity

As previously indicated, the operating environment of this device is severe. Not only must it survive temperature variations of nearly 300°C, but it must do so while maintaining vacuum integrity. During normal operation the device sees 10^{-10} torr internal

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vacuum, 10^{-7} torr external vacuum, and atmospheric pressure at the "hot" connector seal point. In the event of a catastrophic failure elsewhere in the magnet, however, the device differential could exceed 100 psi. A ceramic feedthrough effects the electrical/pressure seal. The ceramic is brazed to a cupronickel header (70%/30% - copper/nickel) which in turn is TIG welded to the detector body using nickel filler. Again, the heavy wall tubing allowed machining of a substantial weld preparation area to permit welding,while minimizing warpage. Cupronickel is utilized for its expansion/contraction characteristics relative to the ceramic insulator.

Components in the matching network and transmission line assemblies also encounter wide temperature variations. Breakage under thermally induced strain was a problem both with the 50 ohm carbon resistor and the twistline at its exit point.

Strain relief for the resistor was accomplished by mounting its terminals to brass cantilevers fabricated from 5-mil shim stock. These tabs allow free expansion and contraction of the resistor without buildup of internal stresses.

In order to secure the twistline connection points and the inductive loop in the matching network, the top section of the feedthrough is potted with epoxy. The wire itself, however, must be strain relieved at the exit point. The space between the twistline and its protective sleeving, therefore, is packed with pure cotton. Cotton has been found to remain flexible at helium temperature and does not allow the epoxy to "wick" in this area. This effects a flexible relief point to prevent breakage of the wire during handling.

Connection to the unpotted resistor is accomplished by plating over the edge of the copper-clad G-10 block.

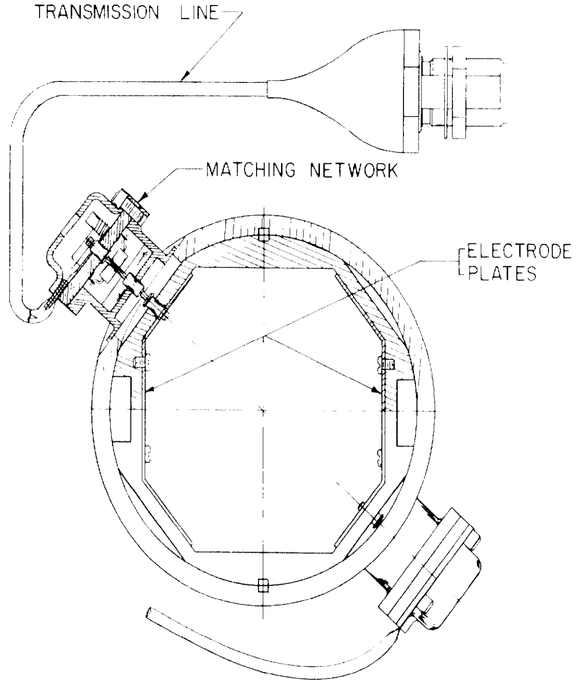

Fig. 2: Horizontal Detection Position

Packaging

Ease of assembly and testing of the beam sensor dictated that it exist as a separate unit for subsequent installation in the Energy Doubler magnets. It was considered to fabricate the device into the beam pipe itself, primarily as a result of space limitations. This proved not only tedious from an assembly standpoint and cumbersome for testing, but, more importantly, threatened those criteria discussed earlier.

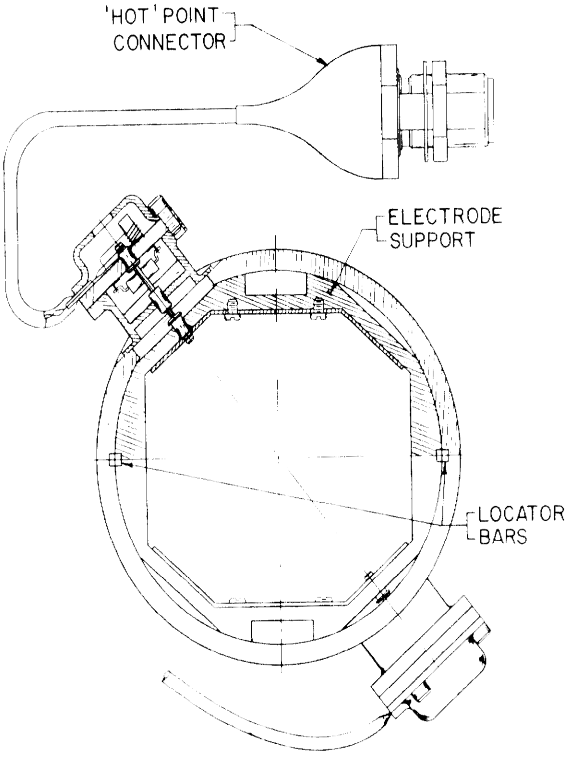

Fig. 3: Vertical Detection Position

The result is a unit 15.56 cm long which is easily handled, and is aligned and welded to the beam pipe during magnet assembly (see Fig. 1). As a result of some redesign in the magnet itself, the device uses less than 8 cm of available space along the beam pipe. Since the detectors are a uni-directional device, that is, they detect off-axis displacement in only one plane, the electrode plates are positioned horizontally and vertically, alternately around the ring as shown in Figs. 2 and 3. Position of the feedthroughs as shown, is 40^{o} off-axis, in line with the device centerline. Placement in this position provides clearance to neighboring quadrupole components.

Repairability

One shortcoming of building a device such as this is its susceptibility to mishandling. Fortunately, the electrodes and electrode supports are well protected by the body itself. The external matching network, however, is prone to failure through accidental abuse. Removal of the entire unit is a difficult job after alignment and welding. For this reason the transmission line assembly (see Fig. 2) has been made to plug onto the ceramic feedthrough. Should damage occur, one or both units can be readily replaced.

III. ELECTRICAL DESIGN

Three sensitivity parameters, directional, intensity and displacement, together with three supplementary electrical parameters, frequency range, VSWR and phase matching, define the major electrical characteristics of the detector. These will be outlined briefly as follows.

Directional Sensitivity (Sd)

The beam detector for the doubler accelerator development activity is required to be nondirectional, i.e., equal voltages must be obtained from the output port for equivalent beams threading the interaction region in the forward or reverse directions. This sets the condition that the ratio of the forward to reverse voltage is unity.

The directional sensitivity, Sd, is therefore:

$$Sd = \left.\frac{Vf}{Vr}\right|_{qf\,=\,qr} = 1$$

where Vf, Vr = developed forward and reverse voltages

qf, qr = beam charge in forward and reverse directions.

For a symmetrical differential capacitive electrode set, the kind selected for the doubler's detector, Sd = 1. Strip transmission line electrodes are examples of the case where Sd>>1, making this type of device very directional, but very useful for future consideration when two beams must be present.

Intensity Sensitivity (Sz)

The requirement that the beam detector operate at low intensity with only a few bunches to produce an adequate signal-to-noise ratio (SNR), coupled with the desirability to minimize the detector's beamline linear dimension and thereby lower the impact on cryostat loading, makes the intensity sensitivity an important design parameter. Specifically, for a total of say 1×10^9 protons contained in 30 similar bunches and each passing the detector's interaction region in 3.0 ns, the peak current, $\frac{dq}{dt}$, available per bunch is about 1.8 ma peak. For processing equipment of moderate cost and complexity to interface with the detector, it has been established that at least 0.5 mV peak is desirable at the input to the processing electronics. With 0.5 mV applied to the processing devices, a SNR of 10 dB is achieved at the lowest expected beam level.

When connecting cables, some as long as 250 meters and producing about 10 dB of loss, are added between the detector and electronics, the detector would be required to produce $0.5 \text{ mV} \times 10^{0.5}$ or 1.6 mV for the same SNR conditions. The detector's minimum intensity sensitivity or mutual impedance defined for a 50 ohm system then becomes:

$$Sz = \frac{V \text{ det pk}}{I \text{ beam pk}} = \frac{1.6 \times 10^{-3}}{1.8 \times 10^{-3}} = 0.9 \text{ ohms, MIN.}$$

The Sz value becomes a valuable guide to characterize system performance and in narrowing the choice of several possible candidate geometries.

Measurements of candidate detectors with various plate geometries and having not more than a 12.7 cm linear dimension (design goal value) were made. These included split plate types, a parallel plate type and a split cylindrical type.

Of the types tested, a truncated parallel plate electrode was selected on the basis of producing at least an Sz value of 1.25 ohms, a larger value than any of the competitive types in the same beampipe and above the requirement by more than 30%. Figs. 2 and 3 show the electrode shape.

Displacement Sensitivity (Sxy)

A 0.5 mm displacement is the desired detection level for doubler measurements. The uncertainty in the electronic systems output quantity when processing ideal input quantities together with the minimum displacement requirement, to a first order, determines the necessary sensitivity of the beam detector. The displacement sensitivity is defined as:

$$Sxy = \frac{20 \text{ Log } \frac{V_1}{V_2}}{\Delta d} \text{ , dB}/\Delta d$$

where V_1, V_2 = electrode voltages

Δd = the displacement causing the change in the V_1/V_2 ratio.

The electronic systems used in conjunction with the beam detectors have uncertainties in the developed position quantities of about 0.3 dB or 3.5% when ideal inputs are applied over a 63 dB amplitude range. The beam detector must therefore produce an output signal change which is greater than the uncertainty when the design minimum value of 0.5 mm displacement takes place. Using the electrode structure shown in Figs. 2 and 3, the electrodes were adjusted relative to the outerbody centerline to optimize as many of the detector's parameters as possible, including the Sd value, Sz value, and the displacement sensitivity. A value of 0.8 dB/mm or 10% change/mm was achieved for a plate separation of 6.35 cm. Considering all relevent factors, particularly the large aperture and the intensity sensitivity, this is considered an adequate value for the detector plate position.

Frequency Range

The doubler beam detector exhibits bandpass electrical characteristics when excited by charge induced short impulse current doublets of the beam. The low frequency corner in the BP condition is 94 MHZ and is the result of the 28 pf plate-to-body and stray capacity and the 50 ohm loading impedance. The upper corner frequency is determined mainly by the cable matching network which couples the twistline to the output connector and the ground elevating inductance, a device to permit single-ended balanced operation of the doubler. The low-pass response characteristic to a repetitive 3 ns wide current pulse is shown in Fig. 4, where the output voltage is seen to be very constant over the range tested (6 to 100 MHZ). After about 130 MHZ, performance deteriorates until at 200 MHZ, as shown in the lowermost trace of Fig. 4, the output is reduced to 70% of its initial value. The operational condition is as shown in the fourth trace from the top, Fig. 4.

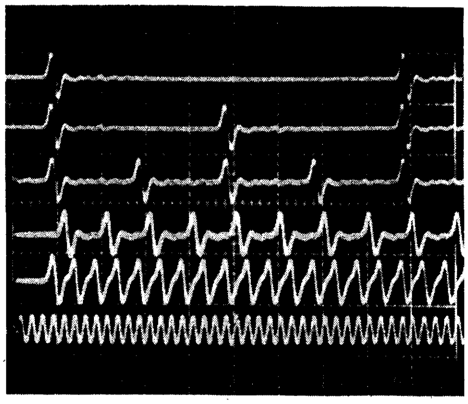

Fig. 4: Detector Response to 3 ns Pulse vs. Pulse PRF.

VSWR

The desirability of a detector with an equivalent internal impedance of 50 ohms becomes increasingly important for the high intensity operation contemplated for the doubler machine. Under high intensity conditions x-ray radiation and maintenance/reliability aspects may preclude attachment of active preamplifiers or matching devices directly to the electrodes. In this case, low impedance (50 ohms) coaxial cables are attached directly to the electrode coupling structures. Some cables are as long as 250 meters; these become the principal transmission medium to safe areas. To circumvent the development of spurious beam signals due to reflective energy, either generated along the cable runs or at the terminating ends, the doubler beam detector's driving point impedance is adjusted to 50 ohms. The beam detector "looks" real from dc to about twice the operational frequency, 106 MHZ, as shown in the VSWR plot of Fig. 5.

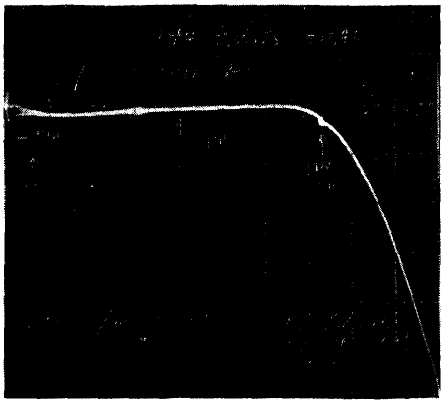

Fig. 5: VSWR Frequency
1st Major Division Below
Reference is 1.2:1

Phase Matching

Processing the two position monitor signals can be accomplished by a choice of methods; the sum and difference hybrid techniques and separate channel amplitude-to-phase conversion methods are common. In order to maintain good accuracy in the resultant processing, the phase of the electrode voltages must be matched. The twistline cables and matching networks are controlled ± 2° from 40 to 63 MHZ to permit tight processing control via either technique.

The following tabulation lists the major parameters of the detector.

Tabulation of Detector Parameters

Type	parallel plate, electrostatic
Intensity Sensitivity	1.25 mV/ma
Directional Sensitivity	1, nondirectional
Displacement Sensitivity	0.8 dB/mm; 10%/mm
Driving point Impedance	50 ohms, nominal
Matching Network	dumping resistor + matching inductor
PRF Frequency Range, pulse	dC - 130 MHZ/W 3.0 ns excitation
Lower cut-off frequency	94 MHZ
Upper cut-off frequency	208 MHZ
Phase Matching	± 2° max between output ports
VSWR	<1.1:1, 10 - 106 MHZ
Coupler, electrode/connector	50 ohm twistline
Electrode length	12.7 cm
Electrode-electrode aperture	6.35 cm
Vacuum seal	Ceramic, coaxial feed-through
X-ray	3 M rad, total dose
Operational temperature range	4°K - 300°K
Beamline	2-7/8" Dia., 304SS
Electrode Supports	Glass, epoxy, G-10

IV. SUMMARY

A series of devices meeting the above parameters, both mechanical and electrical, has been installed in a test segment of the Energy Doubler accelerator. Information obtained has aided in establishing and studying position data required for passing a proton beam through the first string of superconducting magnets at Fermilab.

V. ACKNOWLEDGEMENTS

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