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# THE NAL BEAM SPLITTING SYSTEM

L. W. Oleksiuk, R. A. Andrews, E. J. Bleser, C. H. Rode
National Accelerator Laboratory†
Batavia, Illinois

## Summary

The proton beam extracted from the National Accelerator Laboratory main ring synchrotron is transported through a magnetic switchyard that is designed[1] to carry the external beam to three experimental area targeting stations located 3500 to 5000 ft. from the synchrotron extraction point. Two beam splitting facilities have been recently installed in the switchyard transport system so that all three experimental areas can receive beam simultaneously.

## Introduction

The splitting design adopted at NAL has been to split the beam vertically with an electrostatic wire septum, and then to separate the two split components horizontally by means of a Lambertson iron septum magnet. The alternative choice of a copper septum was felt to be unattractive in both power consumption and device reliability in view of the possible high radiation levels.

A general layout of the NAL external beam switchyard is shown in Reference 2, indicating both the installed splitting stations for diverting beam components to the Proton and Meson Experimental Areas and contemplated splitting stations presently under design. The Meson Area beam line bends 160 milliradians (mr) to the west; the Proton Area beam line bends 100 mr to the east. The splitting system Lambertsons are connected in series with the appropriate bending magnet string and provide the initial 7 or 8 mr of horizontal deflection for each bend. The Neutrino Area beam passes through both sets of Lambertsons in a field-free aperture and is undeflected.

Figure 1 shows elevations of the three beam lines resulting from the insertion of the splitting stations. The original switchyard optical designs and beam elevations were altered in order to simplify the operational aspects of the splitting system.

To accomplish a split, the external beam is deflected from its normal trajectory onto a thin wire septum that forms the ground plane for two opposing cathodes. A representation of a typical splitting station is shown in Figure 2. The diverging electric fields deflect the beam vertically in opposite directions on each side of the wire plane. If the net difference in deflection is larger than the natural vertical divergence of the beam, then the beam is resolved spatially into two components. The natural vertical divergences of the external beam found at the splitting stations are typically ±20 and ±40 microradians, so that the wire septa fields were designed to provide angular separations of ±60 and ±130 microradians. To control the splitting technique, a set of three magnetic deflection systems are utilized to: (1) vary the amount of beam translation at the electrostatic wire plane and thus control the splitting ratio; (2) vary the vertical angle of the beam at the wire septum to minimize losses on the wires; (3) position the two split components for proper insertion into the Lambertson apertures. In addition, the deflection system can send the full beam to any desired experimental area. Lack of space necessitated including intervening quadrupoles in the design of the splitting bump optics. In both installed splitting stations, existing beam line quadrupole doublets were integrated into the bump optics without increasing the complexity of the splitting operation, as is shown schematically in Figure 2.

## The Double Cathode Electrostatic Wire Septum

Figure 3 shows an end view of an electrostatic wire septum. The design provides a grounded array of 0.002 in. tensioned tungsten wires spaced at .05 in. intervals on a precisely aligned support structure. Titanium cathodes are placed on each side of and parallel to the wire plane to provide the diverging electric fields seen by the beam. Typical design parameters are given in Table 1 for the two installed stations.

Figure 4 shows the beam loss regions in the vertical phase space presented by an infinitesimally thin septum 6 metres long. Monte Carlo calculations[2] for this septum geometry indicate that 7-10% of the beam striking the wires would suffer nuclear interactions for a perfectly aligned septum. These interactions occur in the first 2 or 3 feet of the septum. Since the septum typically intercepts 1-2% of a beam at zero divergence, lower limit losses of order $1 \times 10^{-3}$ of the beam are possible at the wire septum. Figure 4 shows that the usual increase in effective septum width due to the beam angular divergence is substantially reduced by the diverging electric field. This effect should keep losses near the lower limit. Calculations indicate that 200 GeV/c particles coulomb scattered from the wires have typical root-mean-square angles 0.24 mr horizontally and ±0.16 mr vertically. This scattering produces a 1 or 2% halo on the beams, most of which is beyond the acceptance of the Lambertson magnets. A halo dump system is planned to intercept this scattered beam to protect the Lambertson magnets.

Figure 4 indicates the effect of adjusting the beam orientation at the wire septum. It also shows that a highly divergent beam can be cleanly split as long as the adjustment of the splitting ratio moves the ellipse along its major axis so that the ellipse slides through the low loss region.

In order to keep both the electric fields on the wire septum and the beam losses low, the beam optical parameter "$\beta$" is maximized at the wire septum. The dependence of electric field strength and beam losses on "$\beta$" for a given module length is

$$E \propto \theta_{div} \propto \frac{1}{\sqrt{\beta}} \propto \frac{1}{\text{beam radius}} \propto \text{losses}.$$

In areas where losses must be kept extremely low, high "β" insertions using split triplets are contemplated for future switchyard installations.

Operating experience with the wire septa with beams of $\sim 10^{12}$ protons per pulse has indicated two effects which are currently under investigation to improve reliability. First, it appears that radiation caused by particles interacting with the thin septum ionizes air in the vicinity of the septum. The high voltage vacuum feedthrough is connected to a surge resistor box feedthrough via an aluminum sphere with air as the insulating medium between the sphere and ground. When the air is ionized, a current loop through the surge resistor results in a voltage drop at the septum. Secondly, a characteristic problem of high voltage insulation in a vacuum, which was masked in the single cathode design, manifests itself in the double cathode geometry. Initial studies indicate that high vacuum field emission discharges occurring spontaneously in the cathode-septum region are due to microscopic whiskers developed on the titanium cathode surface. In the single cathode design, an electron which was field emitted from a whisker would pass between the wires to distant ground plane. There its interactions would have no influence on the behavior of the high field region. However, an electron emitted from a whisker in the double cathode configuration can only terminate its trajectory at the wire plane. This effect causes a steady state current with a corresponding field loss at the septum. Investigations have shown that this effect can be quenched by operating the septum in a vacuum region just below the flow discharge region, typically 0.5 to 2.0 x $10^{-4}$ mm of mercury. This effect is under further investigation, but at present, one is led to believe that at this particular pressure, minute ion currents strike the cathode to erode the titanium whisker growth and so eliminate the field emission. Because the wire septa are located in the switchyard vacuum environment (typically 10-100 microns of Hg), they are at present isolated from the surrounding transport areas by .003 in. titanium windows. Eventually, the windows will be removed and differential pumping will provide the proper vacuum conditions for reliable septum operations.

## Lambertson Septum Design

The development of the iron septum magnet design was predicated on several constraints. The working vertical gap was dropped from the normal 1.5 in. used in the switchyard dipole to a 1.155 in. dimension since the larger dimension was based on maximum horizontal plane emittances in the original switchyard design[1]. The Lambertson modules were expected to be placed in series with the large horizontal dipole arrays in the switchyard, and so the coil numerology was fixed by the gap dimension. The actual parameters of the Lambertson magnets presently installed are shown in Table 2. Figure 5 shows a cross-section of the splitting magnets presently installed in the NAL switchyard.

The magnet core is a laminated 10-foot-long assembly into which the coil package is integrated by encapsulation. The entire magnet is covered with a stainless steel skin which acts as the vacuum chamber. Because the coil power must be led into the vacuum chamber via feedthroughs, the Lambertson coil voltage to ground must be limited so that it is less than 1000 volts due to the risk of glow discharge in the vacuum. The unit has a 5 inch wide pole tip, with magnetic compensation at the pole corners and a notched region of the septum face to increase the good field region. The good field region at 7 kG is ±1.5 in. for $\Delta B/B = \pm .1\%$. Because the deflected beam moves away from the undeflected beam by as much as 2.5 in., the shielded circular apertures are offset from the pole tip centre-line by 1/2 in. (A-type) or 1-1/2 in. (B-type) in order to keep the deflected beam within the good field regions of the pole tip. A circular shielded aperture was used since elimination of sharp corners in the septum region lowered the leakage field. Leakage fields in the circular aperture appeared to have roughly an exponential dependence on the gap field. Measurements of the leakage fields for the P-Split array at 7 kG gave

$$\int B \cdot dl = 500 \text{ Gauss-metres}$$

at the septum surface for five modules. The leakage field is predominantly sextupole. Some sextupole trim magnets will be added to eliminate halo production.

The Lambertson unit to be used with a three-component beam for the 3-way split to the sub-areas of the Proton Experimental Area is presently at the prototype stage. Measurements of a prototype for the downstream 3-way Lambertson with pole tip displacements of ±1.6 in. are summarized in Table 3. It consists of a normal dipole structure in which the coils are bucking, with a 1.9 in. iron septum plate centred between the pole tips and the usual circular aperture in the septum. To provide for the normal deflected beam offset, it is planned to punch the laminations with the opposing pole tip centre lines displaced from one another for the downstream units. Due to saturation effects, quadrupole fields in the symmetrical design and sextupole fields in the asymmetrical design are expected in the circular drift aperture. Extensive magnetic field measurements are in progress.

## Preliminary Splitting Operation Results

Recent operations using the NAL 300 GeV/c slow spill beam have yielded encouraging results for the splitting technique. The Proton Area split station was activated. A beam was split and the two components directed simultaneously some 3000 ft. down the proton line, as well as to the Neutrino targeting area. An indication of the external beam vertical phase space density distribution at the Proton splitting station is shown in Figure 6 as well as the distribution resulting from allowing the beam to strike the wire septum with no electric fields. The figures represent actual displays taken from the beam profile monitor system[3] used in the NAL switchyard for beam diagnostics. In the early split tests described here, a

minimum wire septum loss condition was not achieved due to hardware difficulties. The results shown in Figure 9 show the beam profile monitor display at the Proton Split Lambertsons when a 50%-50% split of 300 GeV/c beam was achieved, but with an angle of attack at the wires of approximately 0.04 mr and a lower-than-nominal angular separation (±0.107 mr). The beam profile results indicate that about 5-6% of the beam was scattered into the iron septum from the coulomb-scattering. This loss can be reduced to the 1-2% level by tuning the angle of attack to zero. Further testing using ion chamber loss monitors for halo investigation are now being carried out to determine the source of the scattered components striking the Lambertson septum region. Detailed Monte Carlo calculations are being undertaken to investigate the dependence of these components on wire electric field, beam divergence and beam angle at the wire septum.

Most recently, the external 300 GeV/c beam was split at the Meson splitting station and one split component transported to the Meson area target. Simultaneous split beam transport to the three experimental areas will be implemented very shortly.

## Acknowledgements

The beam splitting systems described here represent the fruit of much labor by many persons. These include A. Bianchi and R. Krull for meticulous work on the wire septa; F. Hornstra and H. E. Fisk for beam diagnostics and beam survey data; J. McCarthy, L. Bartelson and R. Oberholtzer on power supplies and controls; and J. Simon, J. Grimson and J. Otavka on support and alignment. The magnet fabrication group, under W. Hanson, fabricated the splitting magnet components in what can only be described as their own special time frame of reference, which appeared to most observers to be almost infinitesimal. Sticks and carrots with accompanying schedules were supplied by our director, R. R. Wilson, and his deputies.

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†Operated by Universities Research Association Inc. under the auspices of the U.S.A.E.C.

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2. J. A. MacLachlin, NAL Report TM-324, "Scattering Extraction with the Wire Septum", October 14, 1971.
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TABLE 1. WIRE SEPTA DESIGN PARAMETERS

| Beam Line | Length | Divergence Angle (mr) | Gap | Maximum Momentum GeV/c | Voltage at Maximum Momentum |
|---|---|---|---|---|---|
| Proton Line | 2 x 10'<br>3 x 10' | ±.133<br>±.133 | 1 cm<br>1 cm | 400<br>500 | 86kV<br>72kV |
| Meson Line | 2 x 10' | ±.058 | 2 cm | 300 | 56kV |

TABLE 2. PROTON/MESON SPLIT LAMBERTSON MAGNET PARAMETERS

| | |
|---|---|
| Module Length: | 10 ft. |
| No. Coil Turns: | 12 |
| Coil Cross-Section: | .46" x .46" |
| Coil Resistance: | 14 milliohms |
| Drift Aperture: | 1.50" diameter hole |
| Septum Thickness: | .150" |
| Field Gap: | 1.155" |

| Splitting Magnets | Δθ/Module (mrads) | No. of Modules | Maximum Momentum GeV/c | Field at Max. (kG) | Current/Power at Max. Momentum | |
|---|---|---|---|---|---|---|
| | | | | | Amps | kW |
| Meson Split | 2.0 | 4 | 300 | 6.58 | 1279 | 22.9 |
| Proton Split | 1.4 | 5 | 500 | 7.67 | 1492 | 31.1 |

TABLE 3. DOWNSTREAM 3-WAY LAMBERTSON PROTOTYPE

A. General Parameters

| Air Gap | Septum Plate Thickness | Septum Thickness | Pole ℄ Displacement | Pole Width |
|---|---|---|---|---|
| 0.95" | 1.9" | .200" | ±1.6" | 5.0" |

B. Measured Magnetic Characteristics*

| | Symmetric Geometry (Both Poles Powered) | | | Non-Symmetric Geometry (Top Pole Powered) | | | Decrease in Gap Field When 2 Poles Are Powered (Gauss) |
|---|---|---|---|---|---|---|---|
| Gap Field | Quadrupole Component in Gap (G/in) | Sextupole Component in Gap ($G/in^2$) | Avg. Fringe Quadrupole Component (G/in) | Quadrupole Component in Gap (G/in) | Sextupole Component in Gap ($G/in^2$) | Max. Fringe Field (Gauss) | |
| 5kG | 5.5 | 4.5 | 5 | 3.5 | 4.5 | 20 | 3 |
| 6kG | 6.6 | 5.7 | 7 | 4.1 | 5.1 | 23 | 14 |
| 7kG | 8.4 | 6.8 | 16 | 4.5 | 7.6 | 30 | 24 |

*Measurements based on 2.5 in. good field region in gap.

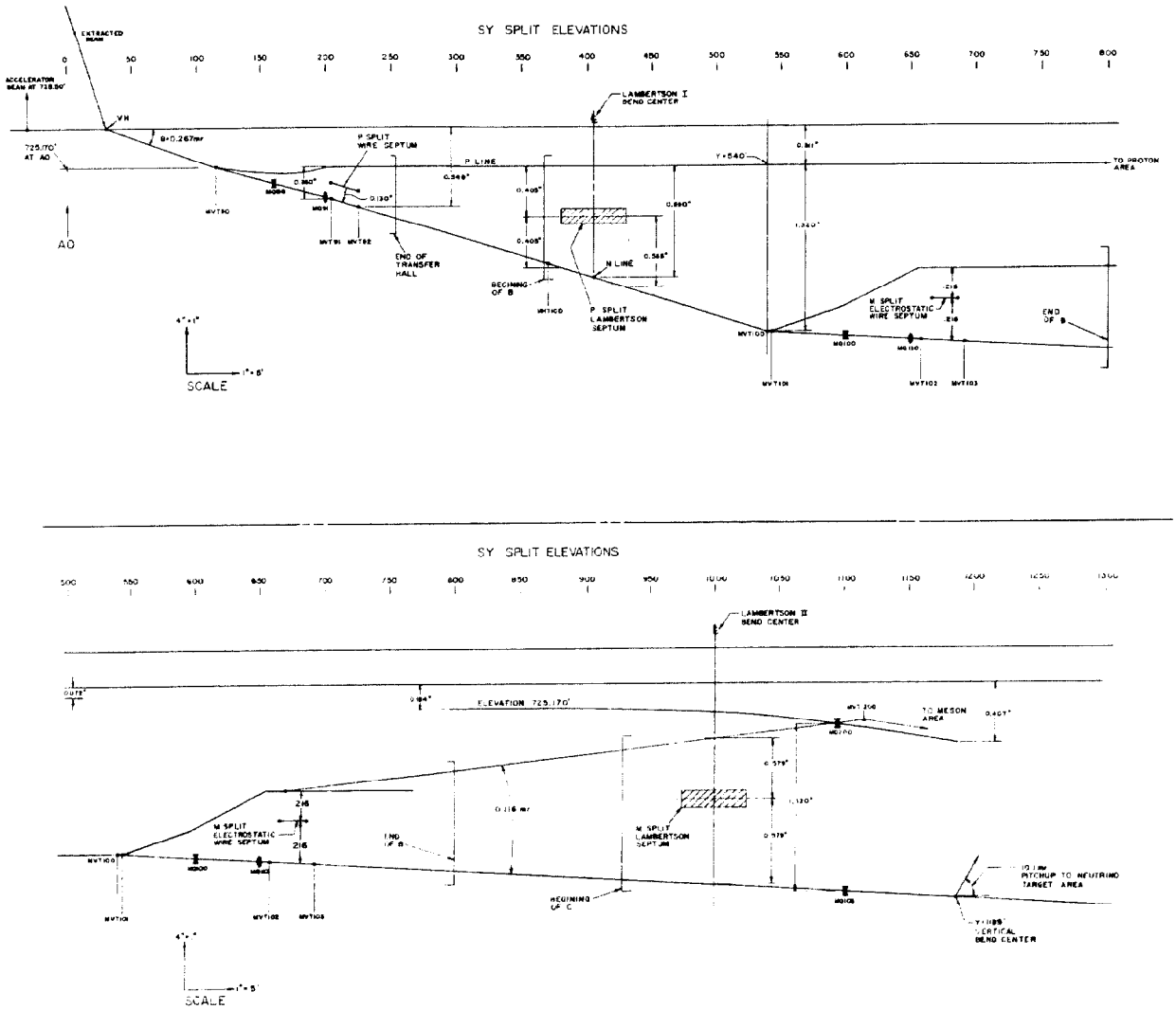



Fig. 1. Split beam centre-line elevations in the switchyard showing the trajectories for 100 % transmission to each area.

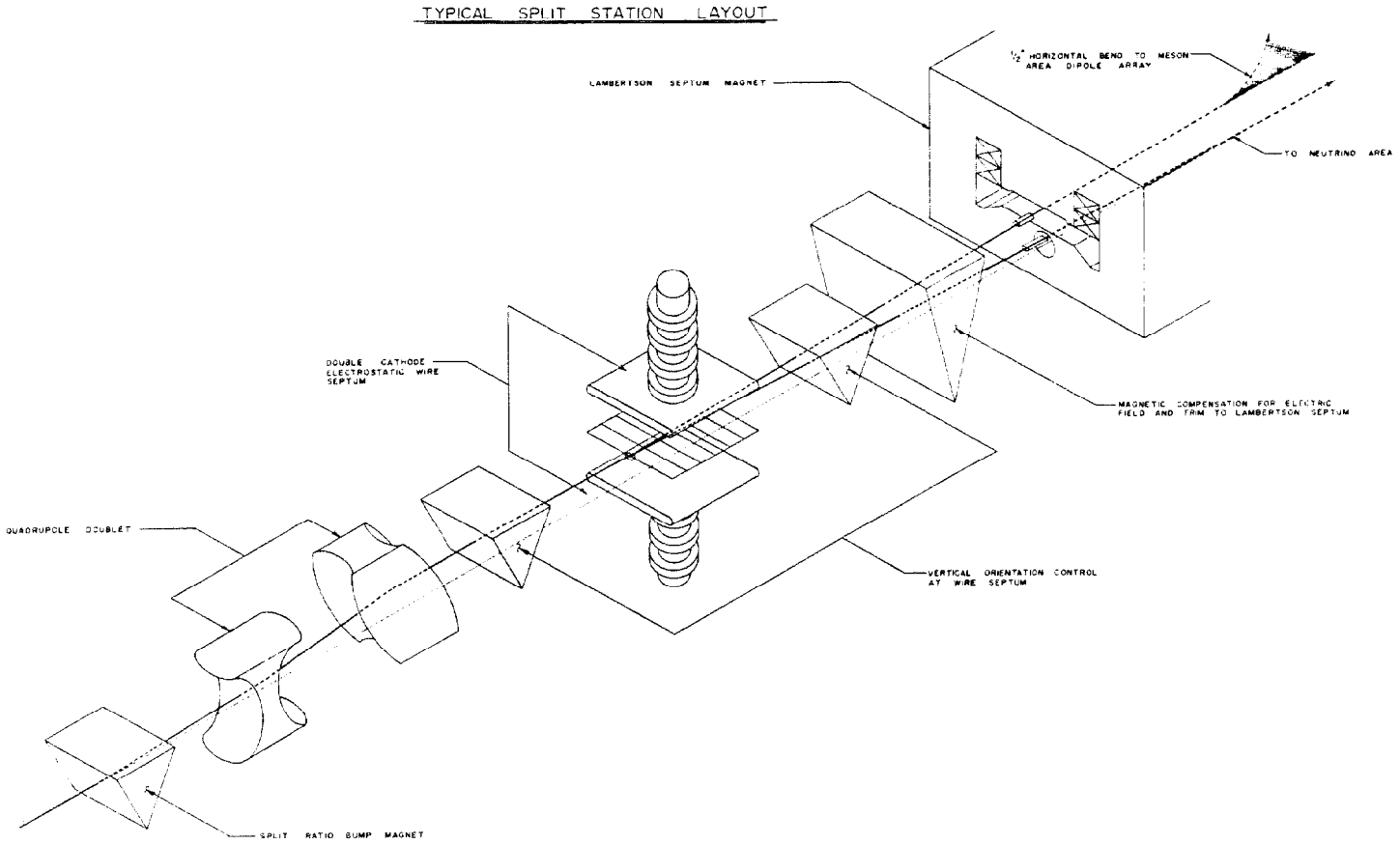



Fig. 2. Isometric schematic of the beam optical techniques used in a splitting station, to control the split ratio, beam losses and insertion into the Lambertson apertures.

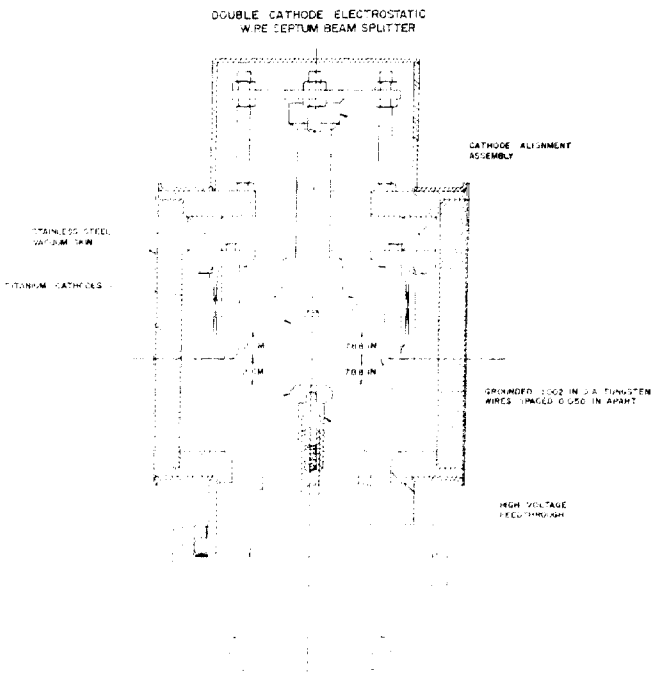



Fig. 3. End view of double cathode wire septum.

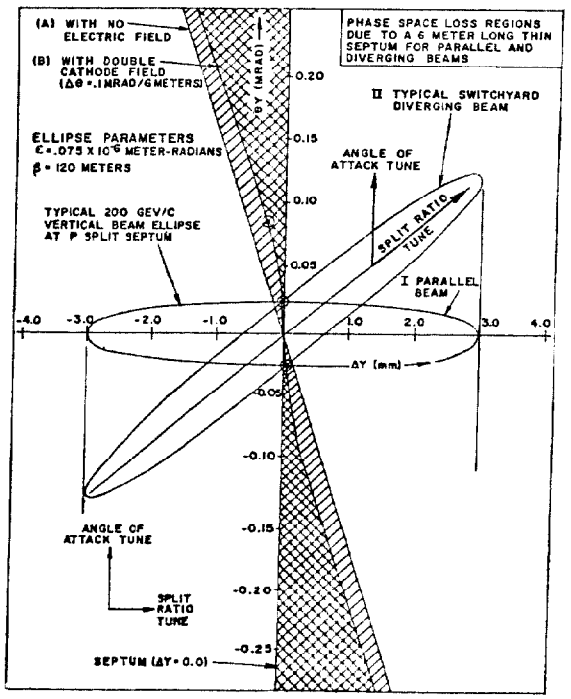
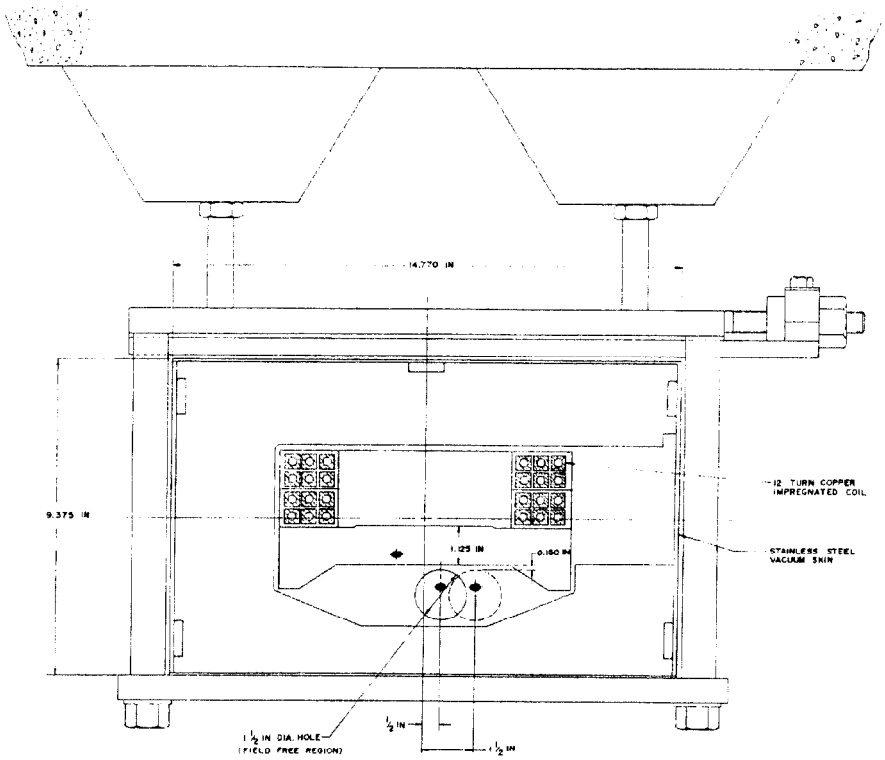
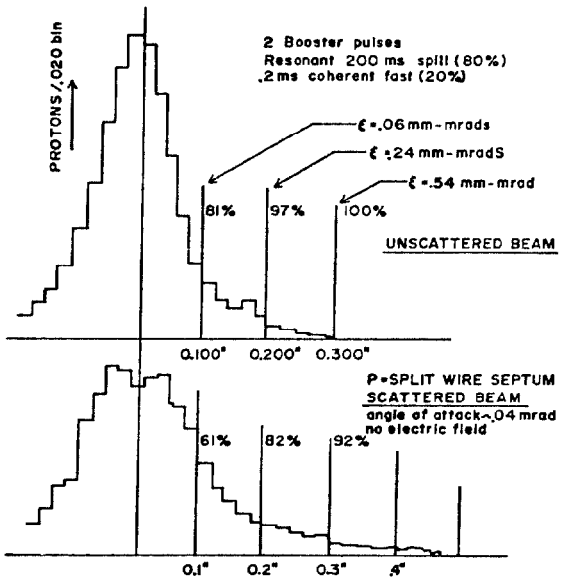



Fig. 4. Vertical phase space beam loss regions for a split station wire septum.



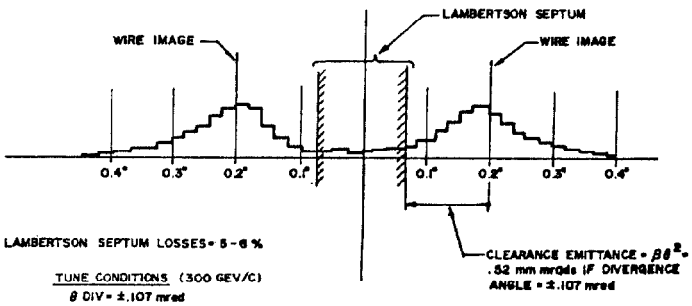

SWITCHYARD LAMBERTSON SEPTUM MAGNET
FOR BEAM SPLITTING SYSTEM

Fig. 5. Cross-section of installed splitting Lambertson magnet.




VERTCAL 300 GEV/C BEAM PROFILES AT P SPLIT LAMBERTSONS

Fig. 6. Vertical beam profile display of a 300 GeV/c extracted slow spill beam before and after striking the P-split wire septum.




SPLIT 300 GEV/C BEAM ENTERING P-SPLIT LAMBERTSON MAGNETS

Fig. 7. Vertical beam profile of a 300 GeV/c split beam observed entering the Lambertson septum in the Proton Line split station.