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QUADS AND BENDING MAGNETS FOR NAL

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I) Introduction

A three day meeting was held at NAL April 8-10 at the suggestion of A. L. Read with a view to choosing provisional parameters for bending magnets and quadrupoles for NAL. The idea was to provide the '68 summer study with something definite to work on in designing beams. The output of the summer study would then include, among other things, revised magnet parameters based on their experience.

Present at the meeting were:

A. L. Read
T. Collins
A. Maschke
A. Roberts
T. White
M. Good
G. Danby

This note is an attempt to summarize, rationalize, and extend somewhat the conclusions of the meeting. All errors are the responsibility of the authors.

II) Conclusions

Four-inch quads, 100" long, and bending magnets with 2" gaps, 120" long, as illustrated in Figure 3 are suggested. The reasons are outlined below.

III) Size of quadrupole apertures, simple scaling

Consider a beam which has been optimized with quadrupoles of a given size. Then ask the question, could the same job be done better with larger or smaller aperture quads?

To answer the question, consider the beam front end shown in Figure 1; quads of aperture R, and length L are located at distance Z_1 and Z_2 from a target.

Imagine the following scaling:

hold Θ_0, p, L fixed;

vary R, Z_1, Z_2 in unison, proportional to a scale factor X

Thus the same limiting ray is kept.

The shape of the trajectory will be held the same. This requires, in each quad, the same bend angle as before (for the same ray), and hence $\Delta p_\perp \sim B_{TIP} dZ \sim B_{TIP} L \sim$ const. Since L is constant, $B_{TIP} \sim$ const. (The above is true in the excellent approximation that each singlet can be treated as a thin lens.)

Thus we have:

$$
\begin{aligned}
B_{TIP} &\sim \text{const.} \\
L &\sim \text{const.} \\
\Delta\omega &\sim \text{const. (solid angle)} \\
p &\sim \text{const.} \\
R &\sim X
\end{aligned}
$$

The number of beams that can be put around a given target will also be constant, if the lateral dimension of the quads scales like X.

What about the power dissipated?

POWER:

Assume first (somewhat unrealistically) that all lateral dimensions scale like X. Then:

$$B_{TIP} \sim \text{const.}$$

Ampere - turns: $NI \sim B_{TIP}\, R \sim X$

Coil Area: $A \sim X^2$ (by assumption)

Current density: $j \sim \frac{NI}{A} \sim \frac{X}{X^2} \sim \frac{1}{X}$

Power density: $\sim \frac{1}{X^2}$

Power: $P \sim$ (power density) (A) $\sim \frac{1}{X^2} \cdot X^2 = \text{const.}$

$$\underline{P \sim \text{const.}}$$

This is admirably simple. Let us examine the same scaling for bending magnets.

IV) <u>Bending Magnets; simple scaling</u>

Again fixed bend angle requires $\Delta p_{\perp} \sim \int B\, dZ \sim B_{TIP} L \sim \text{const.}$

At fixed length, B is constant. The gap, G scales as X

$$G \sim X$$

$$L \sim \text{const.}$$

Therefore, $NI \sim X$

Coil Area: $A \sim X^2$ by assumption

Current density: $j \sim \frac{NI}{A} \sim \frac{X}{X^2} \sim \frac{1}{X}$

Power density: $\sim \frac{1}{X^2}$

Power: $P \sim \left(\frac{1}{X^2}\right) A \sim \text{const.}$

Again, constant power.

V) Discussion: Realistic Scaling

The above idealized discussion would lead to the conclusion that the magnets should be as small as possible, to save on construction cost, for ease in handling, and to make beams shorter. However, the power density goes as $\frac{1}{X^2}$, and this poses a limit. In fact, most bending magnets are already at this limit for reasonable power usage.

If we put the power in terms of power density, one has:

$$P_{\perp} \sim BL \sim \frac{NI}{G} L$$

$$P \sim \left(\frac{NI}{A}\right)^2 AL$$

$$P \sim (NI)^2 \frac{L}{A}$$

$$\sim P_{\perp} \; G \quad \left[\left(\frac{NI}{A}\right) = j\right]$$

$$\boxed{P \sim P_{\perp} \; G \; j}$$

Thus at fixed $P_{\perp}$ and j, the power depends only on the gap. The width of the magnet tends to be constant, since the coil width is fixed by j and B, while the yoke width largely carries the flux passed through the wide coil.

Thus, realistic bending magnets cannot be very narrow. They should, however, have a small gap, set at say half the size of the standard quadrupole aperture.

Quadrupoles should be made small until they run into the power density limitation, at which point they will tend to become of fixed width. Beyond this point, it does not pay to make the aperture smaller, since the number of quads one can crowd around a target then starts to go down.

The tentative choice of 4" quads is felt to be about the "knee" of this curve, and is at the same time large enough to avoid extreme tolerances in manufacture.

VI) Field and Length

The question of capital vs. operating costs should determine the length. One can always double the length and halve the power, independent of all other considerations. Thus this problem splits off from all others (assuming the quads are not touching each other).

Approximately 10 feet long magnets provide flexibility in assembling modules, while keeping sagitta small. The total cost of a long deflection array will not be significantly cheaper if composed of longer blocks.

The optimum operating fields for a given beam from a cost point of view will depend on the availability of capital equipment, power, running efficiency, length of run, etc., and will change with the development of the site. It is suggested that one plan for B_T = 15 kg in quadrupoles, and 20 kg in dipoles, and where practical in design allow space for doubling each unit. This gives twice the capital cost, but half the power, and should bracket the optimum operating range.

VII) Momentum Resolution

For some purposes, it may be desirable to have a momentum spread (at a given lateral point in a momentum analyzed beam) which is sufficiently small to guarantee that an extra π^0 at rest, was not produced so we set

$$\delta p = \frac{\partial p}{\partial x}\,\delta x = m_\pi$$

This may affect the choice of quadrupole size. In general

$$\frac{\partial p}{\partial x} = \frac{\partial p}{\partial \Theta}\,\frac{1}{f_2}$$

where f_2 is the output focal length and $\frac{\partial p}{\partial \Theta}$ is the angular dispersion.

$$\frac{\partial p}{\partial \Theta} \simeq \frac{p}{\Theta}$$

Thus

$$m_\pi \simeq \delta p \simeq \frac{p}{\Theta f_2}\,\delta X_2$$

where δX_2 is the horizontal image size

$$\delta X_2 = \frac{f2}{f_1}\,\delta X_1$$

f_1 is the input focal length and δX_1 is the target size.

Thus:

$$M_\pi \gtrsim \frac{p}{\Theta}\,\frac{\delta X_1}{f_1}$$

or

$$\Theta \geq \frac{p}{M_\pi}\,\frac{\delta X_1}{f_1}$$

Assume 4" quads located so as to intercept $p_\perp \sim 300$ MeV/c @ 300 GeV , i.e.,

$$\theta_0 = 1 \text{ mr} \qquad R = 5 \text{ cm}$$

$$Z_1 = 50 \text{ m}$$

$$f_1 = 3Z_1 = 150 \text{ m} = 15000 \text{ cm}$$

$$\delta X_1 = 0.1 \text{ cm}$$

$$\frac{\delta X_1}{f_1} = \frac{1}{1.5\cdot 10^5}$$

$$\frac{p}{M_\pi} \approx \frac{300 \text{ GeV}}{140 \text{ MrV}} \cong 2\cdot 10^3$$

$$\theta = \frac{2\cdot 10^3}{1.5\cdot 10^5} = 1\cdot 3\cdot 10^{-2} = 14 \text{ mr} \cong 0.7^\circ$$

$$\theta = \frac{BL}{Hp}$$

$$L = \frac{(Hp)\theta}{B} = \left(\frac{3\cdot 10^{11}}{300}\right)\frac{(14\cdot 10^{-3})}{(1.5\cdot 10^4)} = 900 \text{ cm}$$

L = 9 meters (about 4 conventional binding magnets, at 15 kilogauss)

Since this criterion seems to be met with ease, even for the worst case of the highest momentum, it seems to drop out as a consideration.

VIII) Shielding

The effect of quad size on shielding has not really been considered. Presumably smaller quads, closer in, are better, since they allow the first bend to be made earlier, thus getting off-momentum particles out of the beam and into the shield.

IX) Target Layout

The layout sketched in Figure 2 has the following desirable features:

1. Complete independence of all 9 beams from one target.
2. All quadrupoles the same aperture.
3. Angle of beams $\approx$ 500/p radians, i.e., just at edge of forward cone for all momenta.
4. Target distance proportional to momentum, so same c.m. angle bite for all momenta.
5. Current requirement in all quads $\sim$ same, since $\Delta p_{\perp}$ is the same in all beams.

Optimization of an arrangement of this general sort would seem to be a good place to start.

X) Special Magnets

By definition, only conventional magnets have been considered. Figures 3b and 3d illustrate modified conventional magnets, i.e., "thick" septa for quadrupoles and dipoles which can still be operated with normal D.C. power excitation. Very high current density septum beam splitters, C-magnets, and quadrupoles will require techniques which have been unconventional to experimental floors.

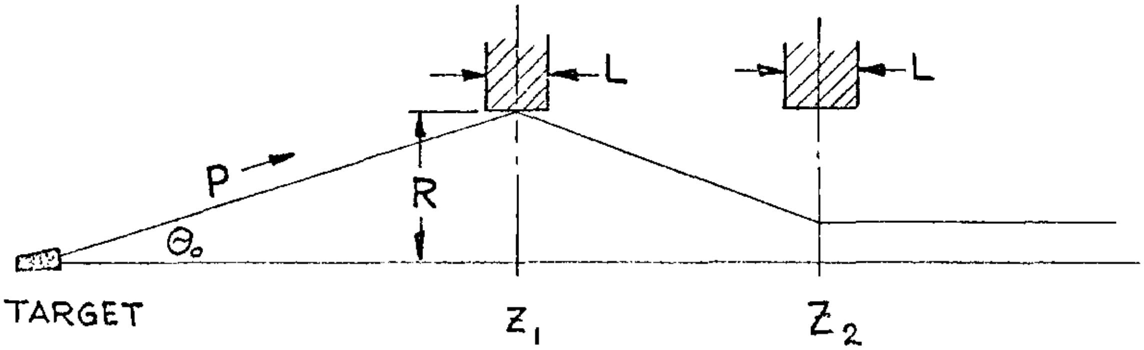


Fig. 1. Beam Front End

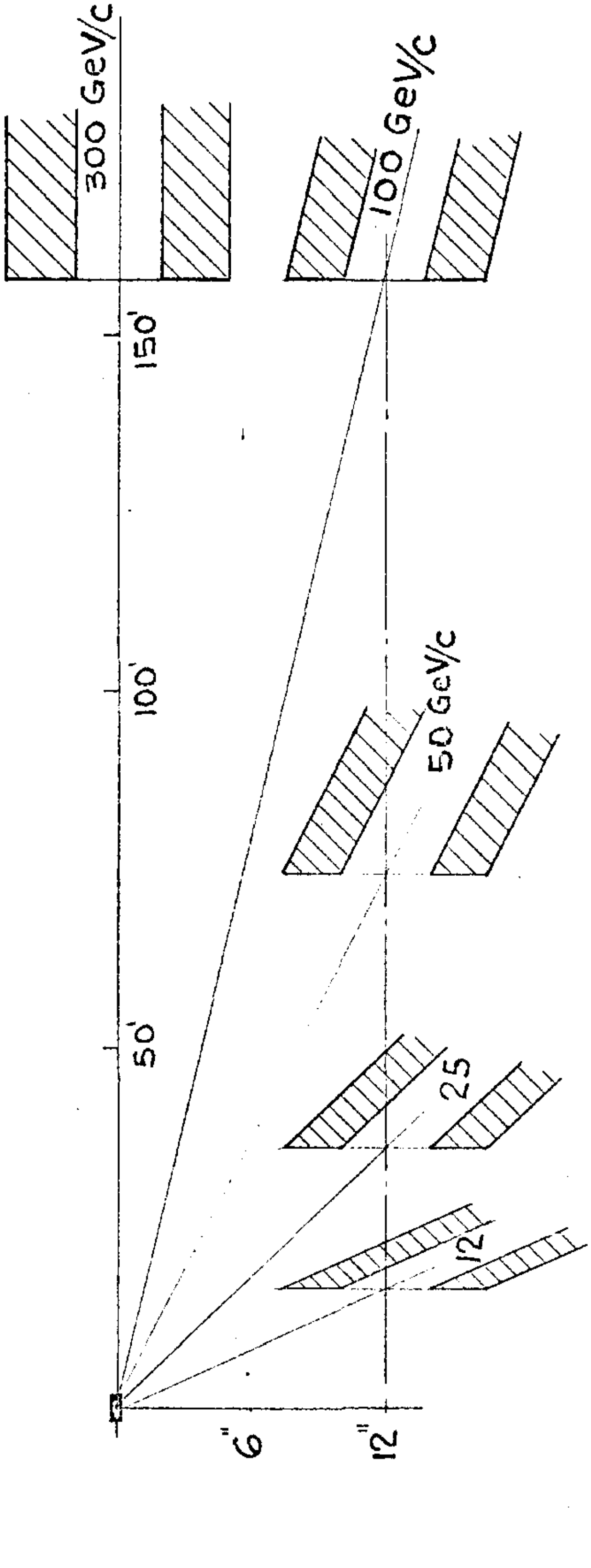


Fig. 2. Horizontal Scale Expansion

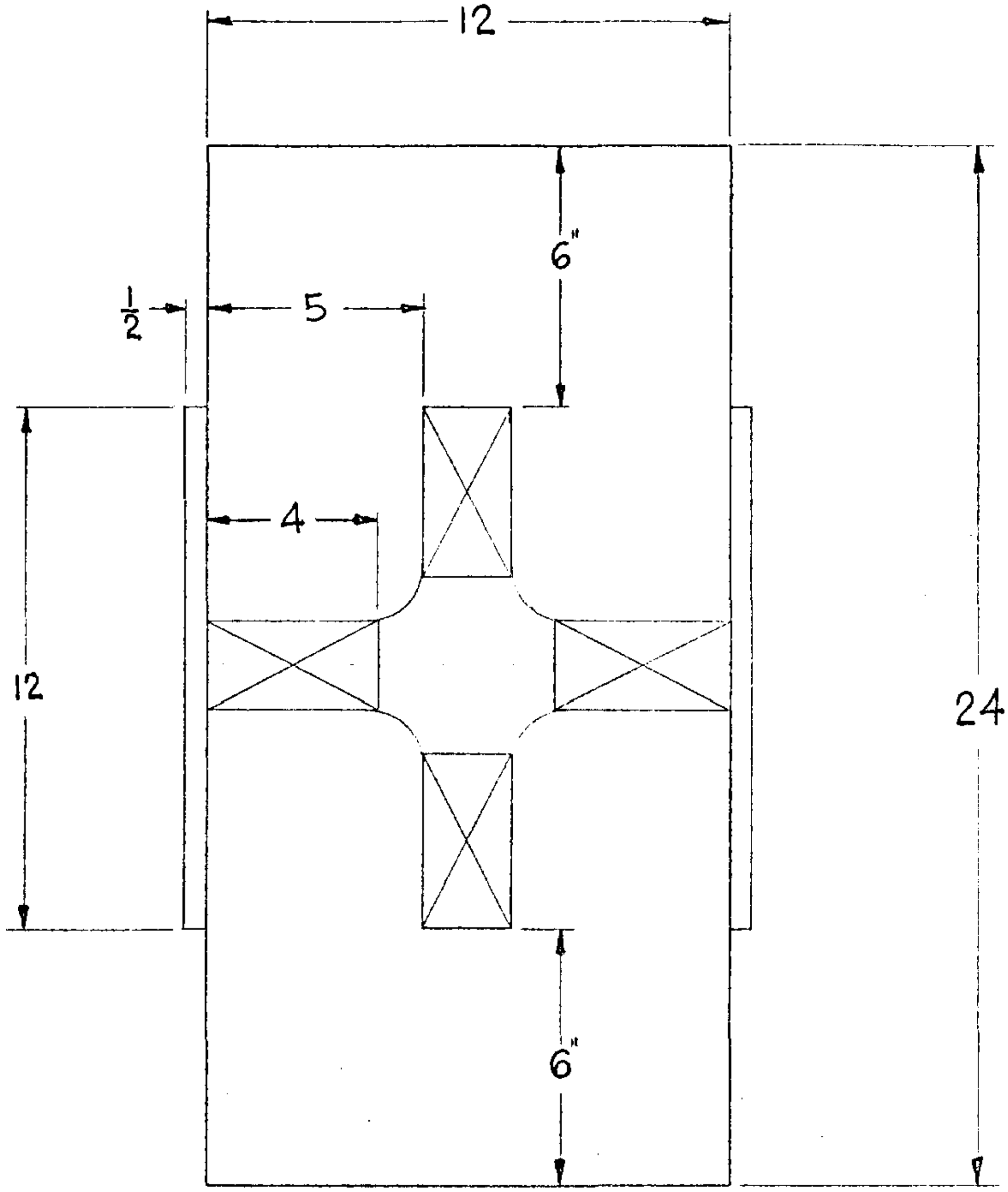


Fig. 3(a). "Front End" Quad

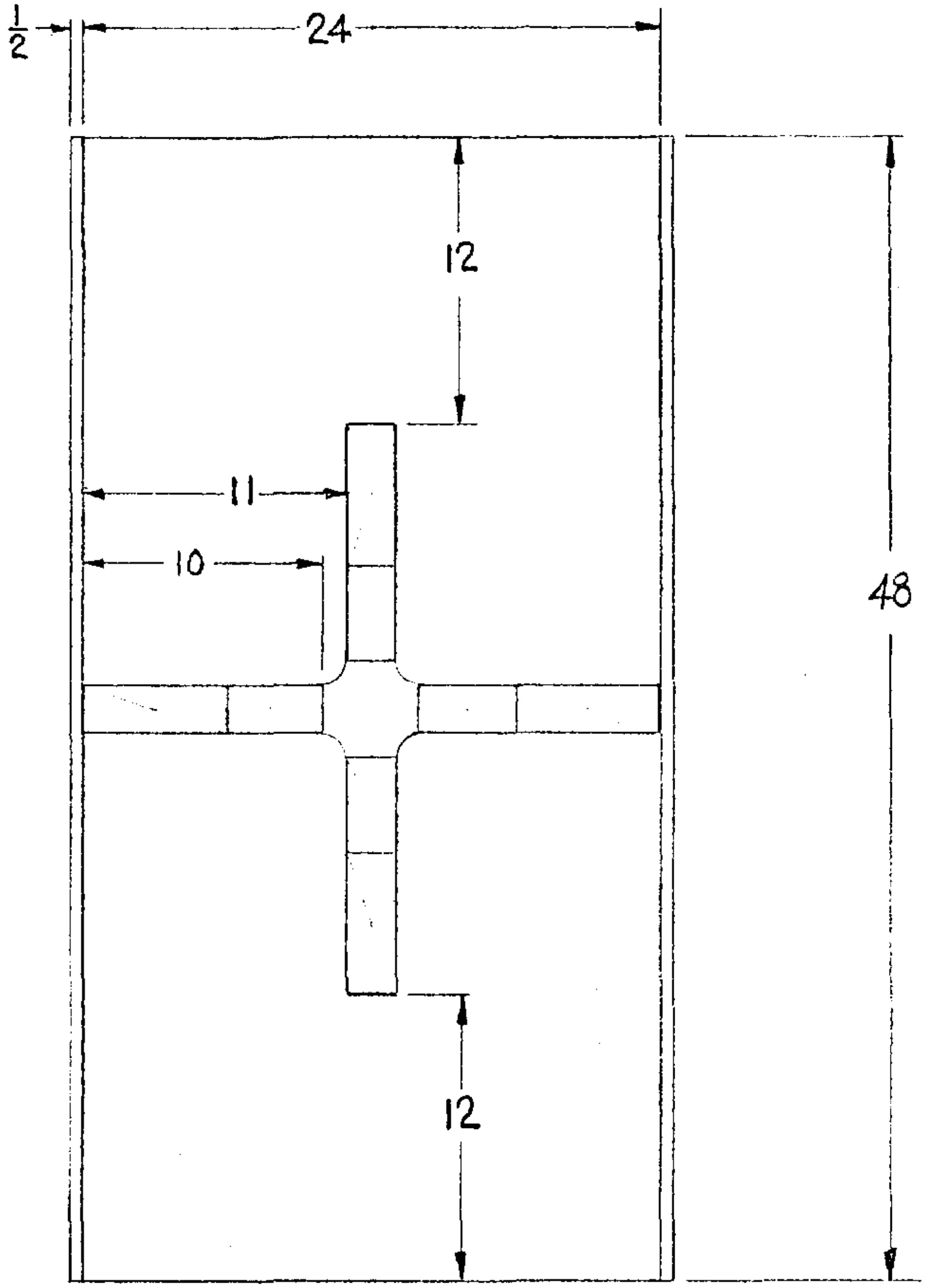
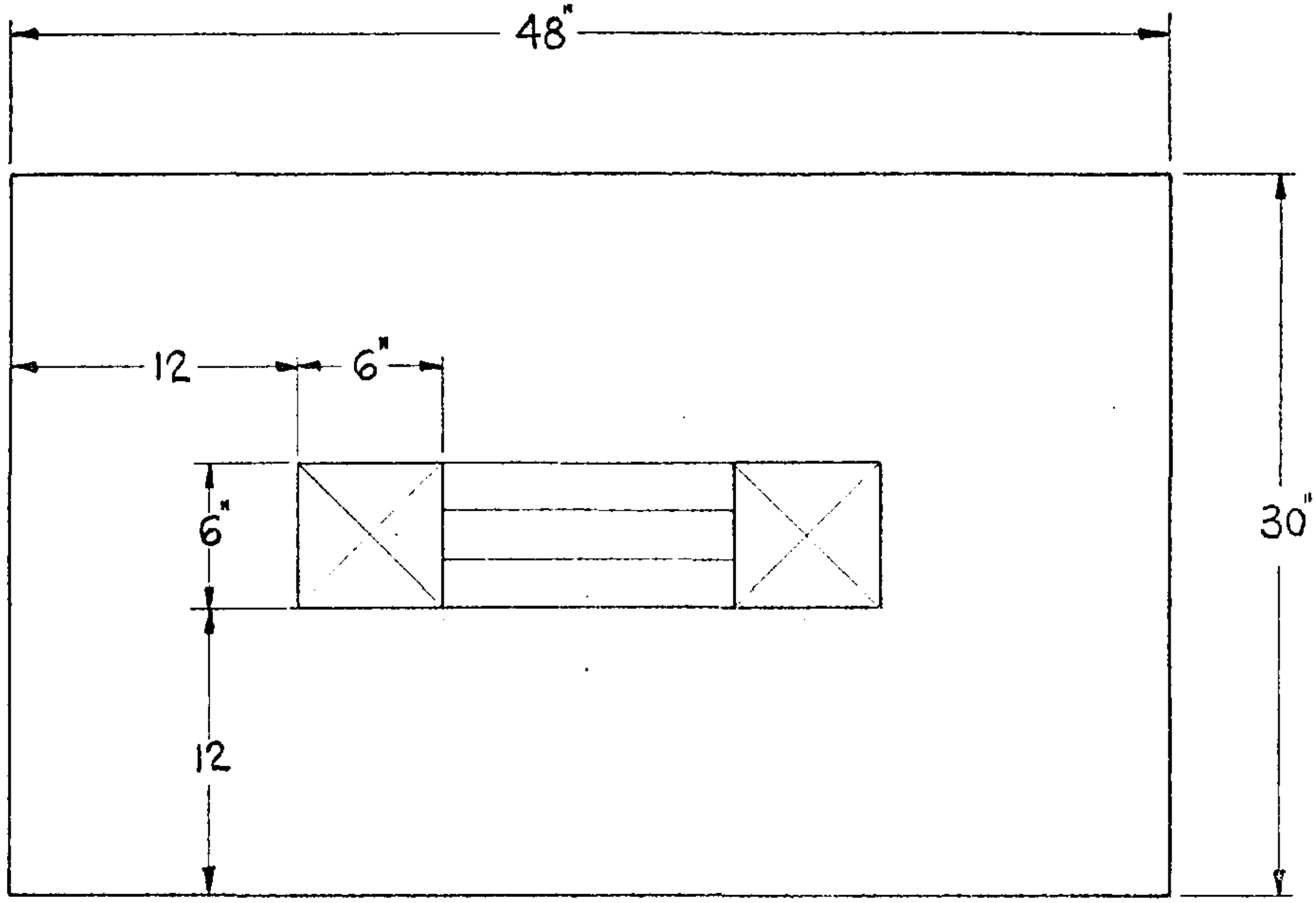


Fig. 3(b). Normal "Low Power" Quad


48"
12
6"
6"
12
30"

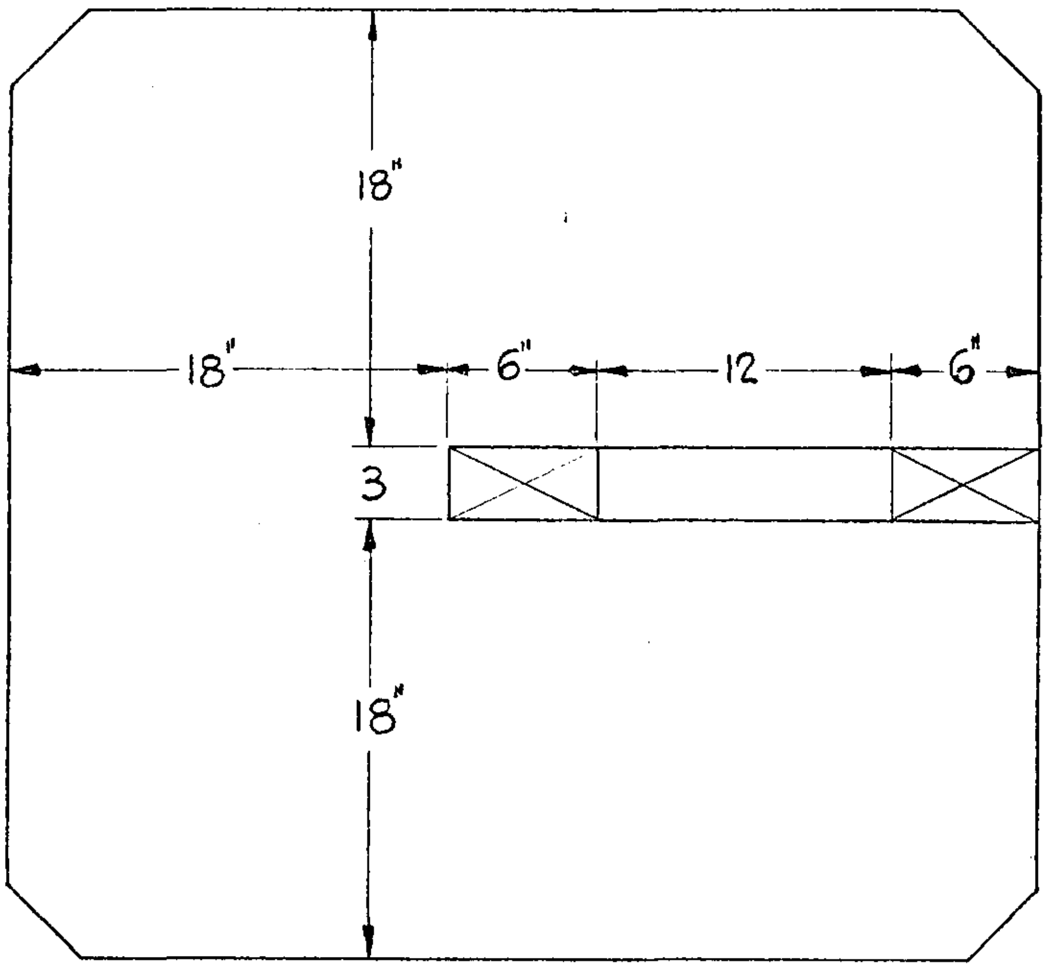


Fig. 3(d). Front End "Septum" C