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BEAM "ABORT" SYSTEM FOR THE MAIN RING

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The conceptual design of a beam "abort" system for the main ring is presented in this report. Further detailed examination of this design using computer calculations is necessary.

General Description

The entire abort system is located in the drift space of a long straight-section (say, EL) and is shown in Figure 1. Four identical pulsed magnets (M1, M2, M3, and M4) are used to bump the beam vertically upward (or downward) onto a beam stopper T1. Secondary particles leaking out of T1 are caught in an aperture stop T2 and protons scattered at a sufficiently large angle from the "boundary layer" of T1 are caught in another beam stopper T3. Protons scattered at small angles from the boundary layer of T1 will pass through the aperture of M4 and spray the immediate downstream main ring magnets. But the number of these protons is expected to be negligibly small.

Pulsed Magnets

These are full-aperture magnets with an aperture of 10 cm (horizontal) x 4 cm (vertical). They will bump the beam vertically by a full vertical aperture in the time of one revolution (20 μsec). These magnets are pulsed in a half-sine wave by discharging a condenser bank through a switching ignitron. To deflect a 200 BeV beam by 4 cm over a 25 m drift length (distance between M1 and M2), the deflection angle is 1.6 mrad and the required strength (field x length) is $B\ell$ = 10.7 kGm. We will make the peak $B\ell$ = 12.3 kGm and the time for a quarter-sine wave $\frac{T}{4}$ = 30 μsec so that the beam will be deflected out of the aperture over the top of the sine wave for the duration of a full revolution. The magnetic field pulse is shown in Figure 2. The parameters of the field pulse are

$$\boxed{\begin{aligned} B_{max} &= 12.3 \text{ kG} \\ \ell &= 1 \text{ m} \\ T &= 120 \ \mu\text{sec} \end{aligned}}$$

The magnet will have a picture frame cross-section with a 4-turn water cooled coil as shown full-scale in Figure 3. The peak current, inductance, and peak stored energy are

$$\boxed{\begin{aligned} I &= 24.5 \text{ kA} \\ L &= 10.1 \ \mu\text{h} \\ U &= 3.02 \text{ kJ} \end{aligned}}$$

The thickness of the core lamination is determined by the flux-penetration time which should be much smaller than the rise time and is given by

$$t = \frac{1}{\pi \times 10^9} \frac{\mu d^2}{\rho}$$

Taking

$$\begin{cases} t = \frac{1}{10} \times 30\ \mu\text{sec} = 3\times10^{-6}\ \text{sec} \\ \mu = \text{permeability} = 1000 \\ \rho = \text{resistivity} = 8\times10^{-5}\,\Omega\text{cm} \end{cases}$$

we obtain d = lamination thickness = 0.0275 cm = 10.8 mil. We shall, therefore, take

$$\boxed{d = 10\ \text{mil}}$$

We have assumed a resistivity for silicon steel which is 5 to 10 times that of low-carbon steel, and, hence, leads to thicker laminations. Also, the lower coersive force of silicon steel gives a more desirable lower remanant field. On the other hand, since these magnets are pulsed only once every 4 seconds, the eddy-current and hysteresis losses are not important considerations. For economy, 3 or 4 mil thick laminations of low-carbon steel are also applicable.

We have indicated solid copper coil conductors with cooling-water holes. Since the skin depth of copper at 8.3 kHz ($= \frac{1}{T}$, T = 120 μsec) is about 0.7 mm, the cooling-water hole could be made rather large, as long as the wall thickness everywhere is more than, say, 2 mm. The copper loss may be reduced by using twisted stranded conductors. But, again, for one pulse every 4 seconds the copper loss is not an important consideration.

The capacity and voltage of the condenser bank for pulsing the magnet are

$$\boxed{\begin{array}{l} C = 36.3\ \mu f \\ V = 12.9\ kV \end{array}}$$

In computing these parameters we have neglected all power losses mentioned above. These losses will increase slightly the necessary energy stored in the condenser bank. Commercial ignitrons exist for which these requirements can be handled by a single tube. The 4 identical magnets should be pulsed in synchronization with field differences of no more than $\frac{\Delta B}{B} = 1\%$. The circuitry for synchronizing the magnets has to be studied. It may be possible to connect all the magnets in series. In that case the coils may have to be redesigned to optimize the parameters of the power supply.

Beam Stopper T1

When a high energy proton enters a material medium it undergoes three different processes.

1. Inelastic nuclear interaction - This process produces a nuclear shower, and if the material is thick enough nearly all the energy of the incident proton will be absorbed

and the proton may be considered "stopped" or "absorbed." This absorption cross-section σ_{abs} is roughly energy independent above a few BeV and has been measured for various materials.

2. Elastic nuclear interaction - This process leads to a scattering of the incident proton without energy loss. The elastic scattering cross-section σ_{el} is generally smaller than σ_{abs} in the energy range of interest and for all except the heaviest materials.

3. Multiple Coulomb scattering from atomic electrons - This results in an energy loss and produces a spread in lateral displacement and angle. The root-mean-square one-dimensional projected scattering angle and displacement are given by

$$\left\{\begin{aligned} \theta_{rms} &= \frac{0.015}{\beta p}\sqrt{\frac{L}{L_{rad}}(1+\varepsilon)} \\ x_{rms} &= \frac{L}{\sqrt{3}}\,\theta_{rms} \\ \varepsilon &= 0.14 + 0.06\,\log_{10}\left(\frac{L}{L_{rad}}\right) \end{aligned}\right.$$

where

$$\left\{\begin{aligned} \beta &= \frac{v}{c} \text{ of incident proton} \\ p &= \text{momentum of incident proton in BeV/c} \\ L &= \text{length of material traversed} \\ L_{rad} &= \text{radiation length of material (related to the atomic number)} \end{aligned}\right.$$

To make a very crude estimate of the number and mean angle of protons scattered out from the boundary layer of the stopper we make the following assumptions and approximations.

(a) The elastic nuclear scattering is neglected. This approximation is fairly good for light stopper materials and not so good for heavy materials.

(b) The energy loss due to multiple Coulomb scattering is irrelevant for our application and is, therefore, neglected.

(c) The screening parameter ε is small compared to unity and is neglected. Thus we have

$$\theta_{rms} = \frac{0.015}{\beta p} \sqrt{\frac{L}{L_{rad}}}, \quad x_{rms} = \frac{L}{\sqrt{3}} \theta_{rms} = \frac{8.66 \times 10^{-3}}{\beta p} \frac{L^{3/2}}{L_{rad}^{1/2}}$$

(d) All protons after traversing the same distance in the stopper material have the same lateral displacement $\pm x_{rms}$ and angle $\pm \theta_{rms}$. These assumptions should be fairly good on the average.

(e) We assumed an infinitely long stopper as shown in Figure 4. This is a very good approximation for the actual stopper.

(f) The incident beam extends over a width Δx across the incident end of the stopper having a uniform linear density λ across Δx (total number of incident protons $= \lambda \Delta x$) and travelling parallel to the edge of the stopper.

This special case when applied as an average is all that is needed.

Under these assumptions and approximations, the total number of protons scattered out of the boundary layer of the stopper is

$$\frac{\lambda}{2}\int_0^\infty e^{-\frac{L}{L_{abs}}}\, dx_{rms}$$

$$= \lambda\, \frac{6.5\text{x}10^{-3}}{\beta p}\, \frac{L_{abs}^{\ 3/2}}{L_{rad}^{\ 1/2}} \int_0^\infty \sqrt{u}\, e^{-u}\, du$$

$$= \lambda\, \frac{5.8\text{x}10^{-3}}{\beta p}\, \frac{L_{abs}^{\ 3/2}}{L_{rad}^{\ 1/2}}$$

where $u \equiv \frac{L}{L_{abs}}$ and L_{abs} is the nuclear absorption length calculated from measured absorption cross-section σ_{abs}. The fraction of the incident beam scattered out is, therefore

$$F = \frac{1}{\Delta x}\, \frac{5.8\text{x}10^{-3}}{\beta p}\, \frac{L_{abs}^{\ 3/2}}{L_{rad}^{\ 1/2}}$$

The mean angle of the protons scattered out is given by

$$\overline{\theta} = \frac{1}{\lambda F \Delta x}\, \frac{\lambda}{2}\int_0^\infty \theta_{rms}\, e^{-\frac{L}{L_{abs}}}\, dx_{rms}$$

$$= \frac{1}{F\Delta x}\, \frac{0.97\text{x}10^{-4}}{(\beta p)^2}\, \frac{L_{abs}^{\ 2}}{L_{rad}} \int_0^\infty u\, e^{-u}\, du = \frac{16.9\text{x}10^{-3}}{\beta p} \sqrt{\frac{L_{abs}}{L_{rad}}}$$

Taking Δx = 1 cm, p = 200 BeV/c (hence $\beta \approx 1$) for various stopper material we get

Table 1

	L_{abs}(cm)	L_{rad}(cm)	F(%)	$\bar{\theta}$(mrad)
Li	104.0	148.0	0.25	0.071
Be	36.9	34.7	0.11	0.087
Al	35.4	8.9	0.20	0.17
Fe	15.2*	1.8	0.13	0.25
Cu	13.9	1.34	0.13	0.27
W	9.7*	0.36	0.14	0.44
Pb	17.3	0.58	0.27	0.46
U	10.9*	0.32	0.18	0.49

*Interpolated values.

Several conclusions can be drawn from the above calculations and results.

1. If the beam height is h cm and the beam is bumped at a rate of y cm/turn onto the stopper only a fraction $\frac{h}{y}$ of the entire circumference of the beam will suffer scattering in the boundary layer. The other part of the circumference of beam will hit the stopper far inside and be totally "stopped." For this $\frac{h}{y}$ fraction of beam on the average $\Delta x = \frac{h}{2}$. Since F is inversely proportional to Δx the fraction of the total beam scattered out is $\frac{h}{y} \times \frac{F}{h/2} = \frac{2F}{y}$

and is independent of the beam height. Moreover, for a given rate of rise of the bump magnet field y is proportional to $\frac{1}{p}$, and since F is also proportional to $\frac{1}{p}$ the fraction of total beam scattered out is independent of p. At 200 BeV, y = 4 cm/turn and we get

$$\boxed{\text{Fraction of total beam scattered out} = \frac{F}{2}}$$

2. Larger $\bar{\theta}$ is more desirable, because protons scattered at sufficiently large angles will be caught by stopper T3. Beryllium gives the smallest F but also a very small $\bar{\theta}$. Iron, copper, and tungsten give much larger $\bar{\theta}$ without significantly increasing F, and are, therefore, good choices of stopper material. The stopper should be about 10 L_{abs} long.

3. Figure 5 shows the cross-section of an iron stopper 1.5 m long with a tungsten boundary layer 3 mm thick. This thickness is slightly larger than the value of x_{rms} for W with L = 10 L_{abs} and p = 50 BeV/c. Since $\bar{\theta}$ is proportional to $\frac{1}{p}$, below 50 BeV/c $\bar{\theta}$ is sufficiently large even for Fe. There is, therefore, no need in making the W boundary layer any thicker. Figure 5 shows a picture frame cross-section. Although only the top frame acts as the active stopper, the other 3 sides may serve to stop stray primary and secondary particles and give mechanical rigidity to the structure.

4. The magnitudes of L_{rad} and $\bar{\theta}$ given in Table 1

indicate the need for extreme flatness of the boundary layer surface. Local roughness should be less than 0.1 mrad extending over, say, 1 cm; namely, the surface should be flat to better than 10^{-3} mm = 0.04 mil. This is also the required alignment sensitivity and stability. The alignment itself can only be done on the real proton beam by maximizing the efficiency of the stopper.

5. To abort beam at lower momenta, we should maintain the same rate of rise of bump magnet field, except the field should be clamped at a value approximately 12 kG x $\frac{p(\mathrm{BeV/c})}{200}$ so that the beam is not deflected excessively to go over the top of the stopper.

6. With this abort system the fraction of beam scattered out of T1 is roughly $\frac{F}{2}$ = 0.07% for W. Depending on $\overline{\theta}$, hence the beam momentum, less than $\frac{1}{2}$ of the scattered beam or, say, 0.03% of the total beam will not be caught by T3. Since as a long-time average no more than 1% of the design beam intensity (1.5×10^{13} p/sec) will be aborted at 200 BeV, only less than 3×10^{-6} of the design beam intensity which corresponds to only 1.5 W of beam power will pass through M4 and spray the immediately downstream ring magnets. This should cause little or no concern.

Stoppers T2 and T3

There is no special consideration for the design of stoppers T2 and T3. They could be made of iron and have a picture frame cross-section with a 10 cm (horizontal) x 4 cm (vertical) opening. T3 should be about 1.5 m long and T2 about 1 m long. The lateral dimensions of these stoppers should, however, be much larger than those of T1. Overall lateral dimensions roughly equal to those of the main ring magnets; namely, 25 inch (horizontal) x 16 inch (vertical) would be appropriate.

Further Studies

1. The approximations and assumptions made for calculating the scattering in the boundary layer of stopper T1 are very crude indeed. More exact computations using a computing machine are needed.

2. When a full intensity pulse (5×10^{13} protons) at 200 BeV is bumped onto the stopper roughly 1.7 MJ of beam energy is suddenly dumped into the stopper. The effect of this thermal shock should be carefully studied and necessary design features for handling the heat dissipation should be worked out.

3. The induced radioactivity and the radiation level in the neighborhood of the stoppers could be rather high. Necessary shielding and handling equipment should be studied and designed.

4. To increase the effectiveness of T3, it is advantageous to increase the separation between M3 and M4, and reduce the separation between M1 and M2 correspondingly. To do this, magnets M1 and M2 will have to have a different strength than that of M3 and M4. Since the effectiveness of

T3 is only of secondary importance, the additional complication introduced by this arrangement may not be justified.

Acknowledgment

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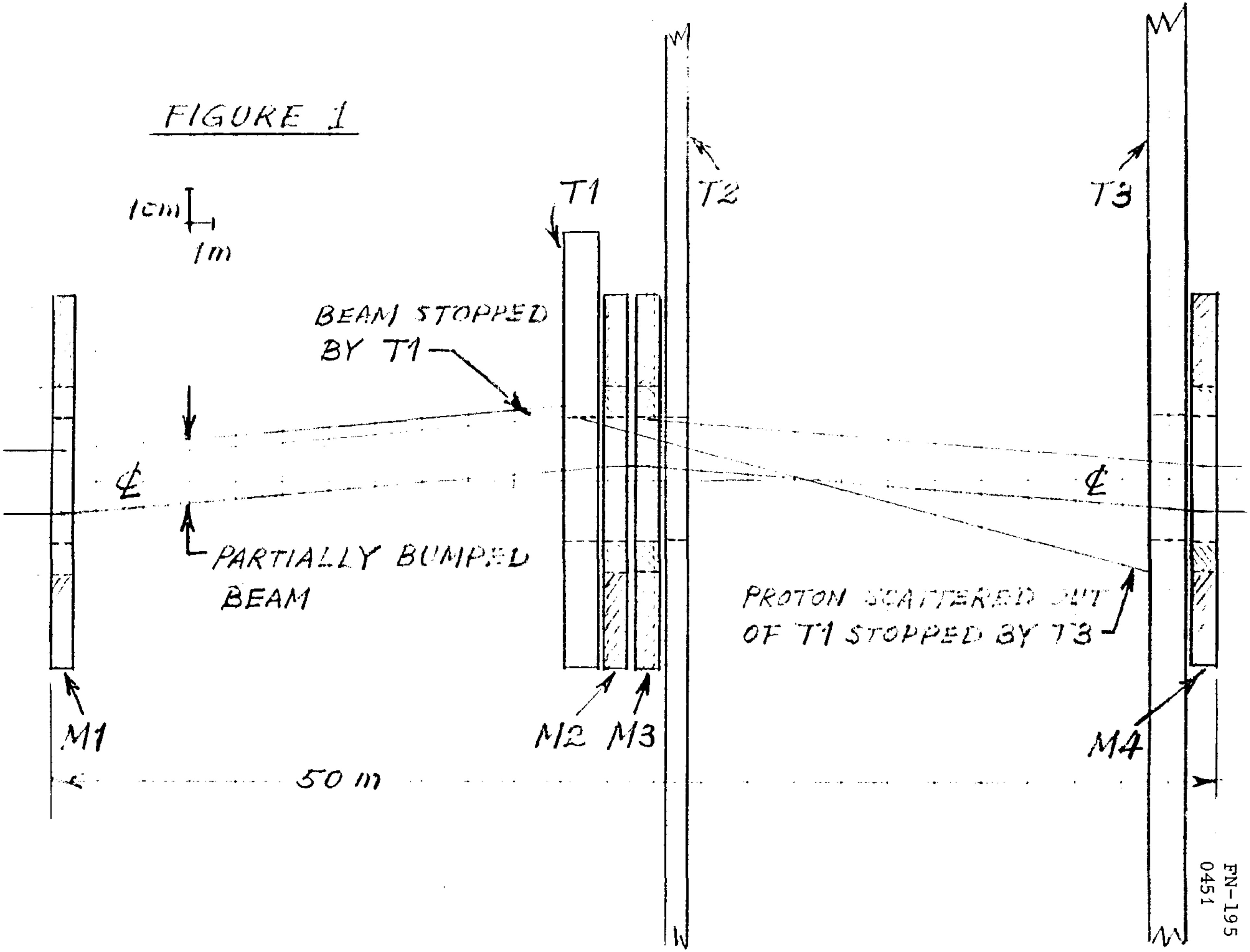
FIGURE 1


1cm
1m
T1
T2
T3
BEAM STOPPED BY T1
PARTIALLY BUMPED BEAM
PROTON SCATTERED OUT OF T1 STOPPED BY T3
M1
M2
M3
M4
50 m

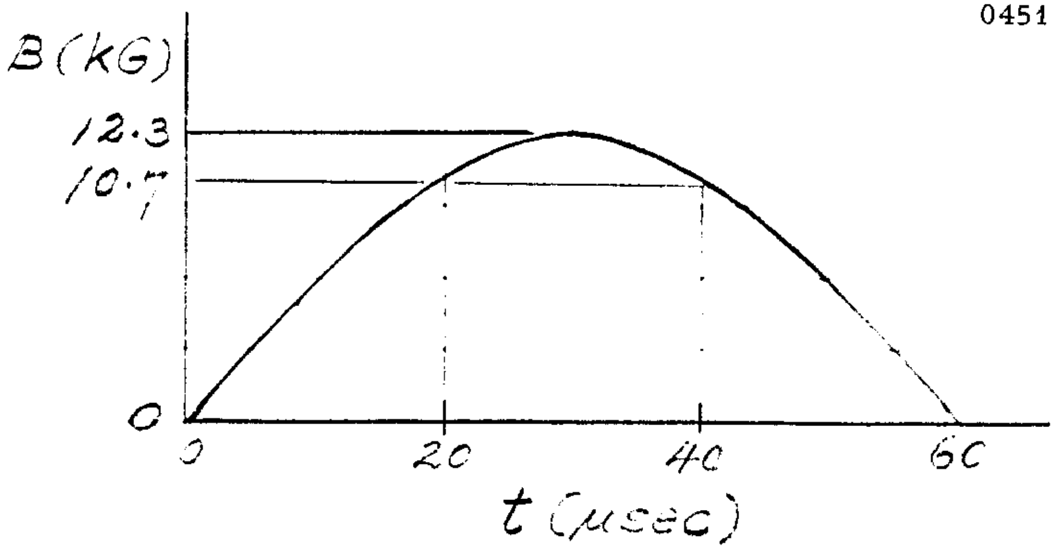


FIGURE 2

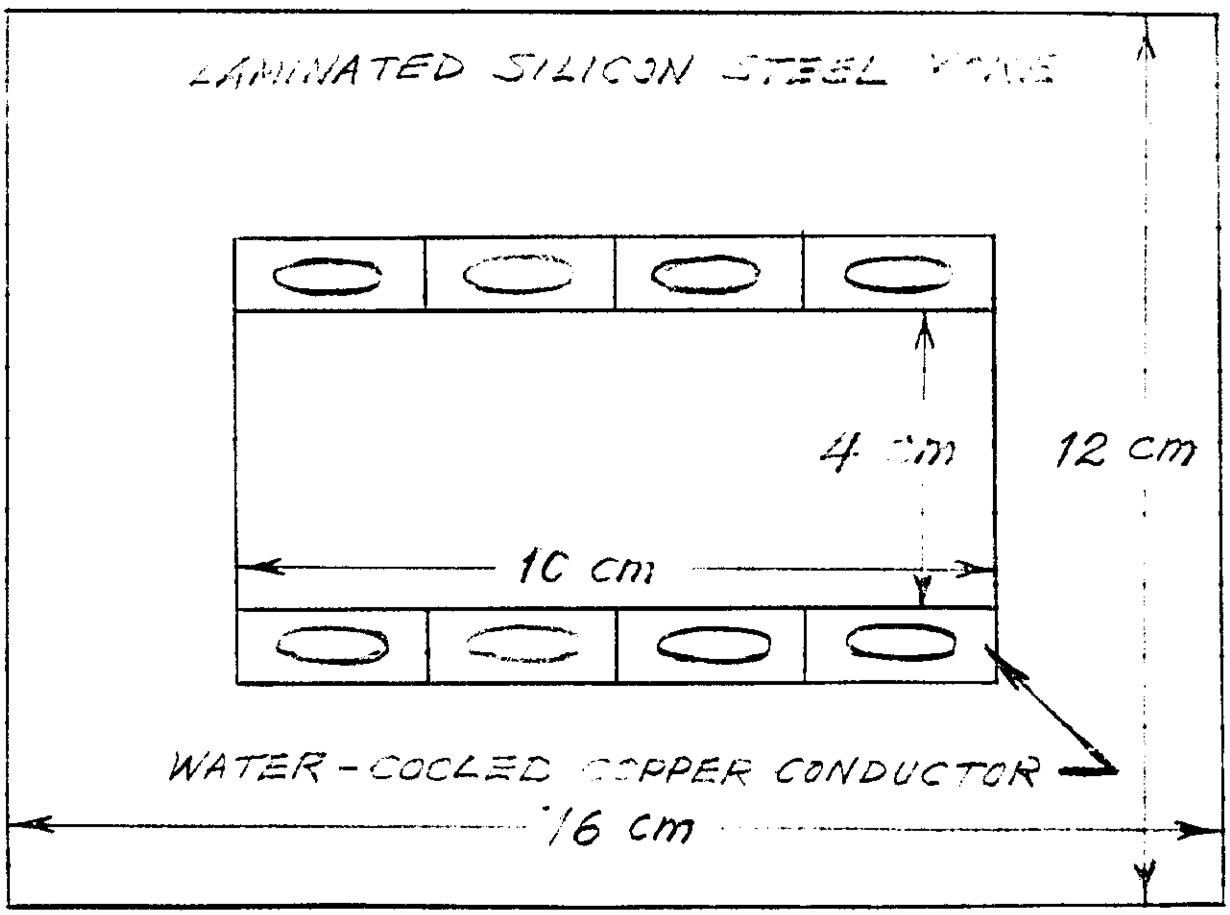


FIGURE 3

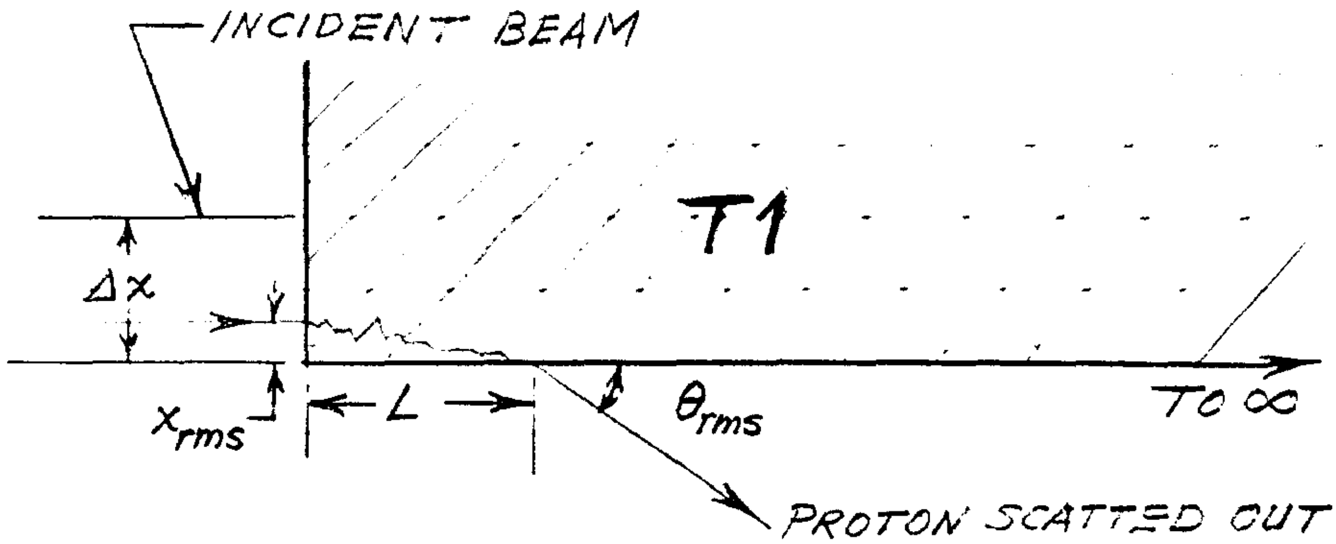


FIGURE 4

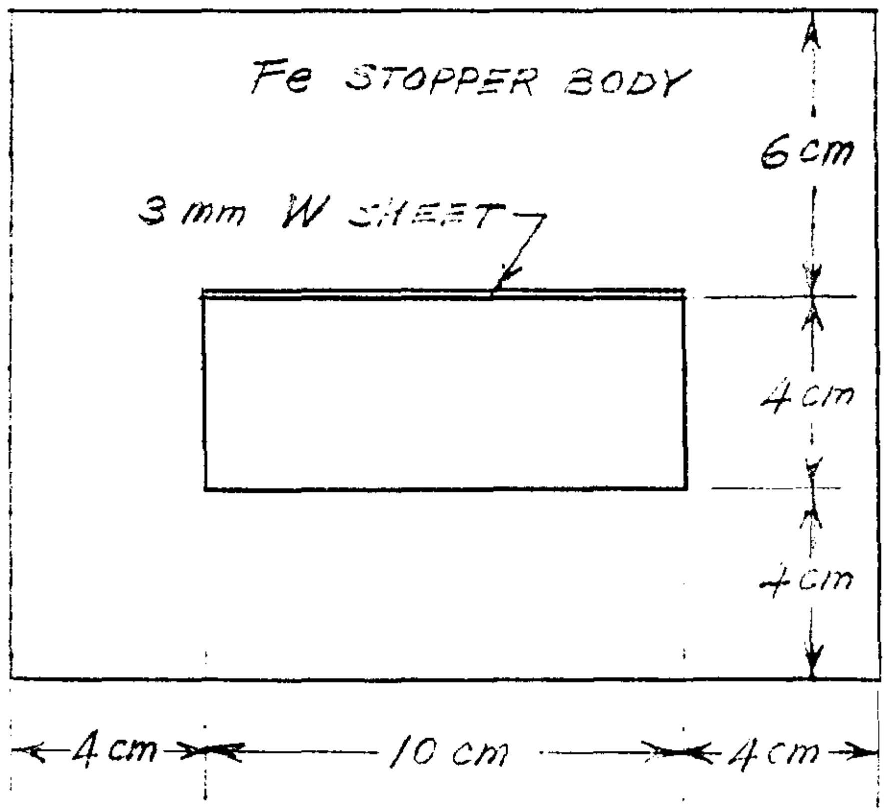


FIGURE 5