11. BEAM-ABORT SYSTEM

11.1 Requirements and General Design

Detailed studies have shown that if even a tiny fraction of the 2×10^{13} protons circulating in the ring interact in the nearby solid material, for example, in the vacuum-chamber wall or injection or extraction devices, then a disruptive quench of one or more of the superconducting magnets will likely result. It is therefore imperative that a beam-abort system exist that can anticipate the imminent occurrence of such quench-inducing losses and cleanly dispose of the beam before they are allowed to happen.

Clearly the most effective strategy is one of prompt single-turn extraction to an external beam dump. The basic elements of the abort system will therefore consist of a fast-rise full-aperture kicker followed by a Lambertson septum magnet and a magnetic beam channel to an external dump. The elements of the abort system are intermeshed with elements of a straight-section bump (discussed in Section 13) used for radiation protection of the downstream superconducting magnets. The effect of beam lost on the magnetic septum and collimators inside the magnets is reduced in this way. Estimates indicate that a few times 10^{11} protons can be lost on the septum. Then the extraction inefficiency of the abort system should be less than 1%. For operation in the $\bar{p}p$ collider mode, an abort for the backward moving $\bar{p}$'s is also required. Since the expected number of $\bar{p}$'s is less than 1×10^{11}, a considerably larger inefficiency can be tolerated; a fast kick into the face of a dump block placed several centimeters from the closed orbit will suffice.

The signal to trigger the beam abort will be generated by any one of the following devices: loss monitors viewing aperture stops at various locations around the ring; fast beam-position and beam-size detectors; power-supply malfunction detectors; magnet quench detectors. The circulating beam will have a gap to accommodate the rise time of the kicker; only 12 Booster batches will be injected into the Main Ring, giving a 1.9-μs gap Once an abort condition is recognized by a detector somewhere around the ring, complete beam disposal can be accomplished in less than 60 μs.

In a previous report[1] two possible solutions for the forward abort geometry were proposed. Further study has shown a solution grouping the elements closely to be very desirable. The geometry described here places the entire forward and backward abort systems as close as possible to the same long straight section. This system has the advantages that the beam does not travel as far during abort and that it conserves valuable long straight-section space. It also allows more flexibility in $\bar{p}$ and p bunch distributions and in the arrangement of functions in the long straight sections. The use of fast kickers with peak fields of 3 kG allows efficient long straight-section design. A conceptual design of a 3-kG kicker and pulsing system is described in this section.

The location of the p and $\bar{p}$ abort systems in long straight-section C is shown in the layout sketch of Fig. 1-2. In Fig. 11-1 we show the location of all the elements of the abort system and the calculated abort orbit. A plan of straight-section C itself is given in Fig. 11-2.

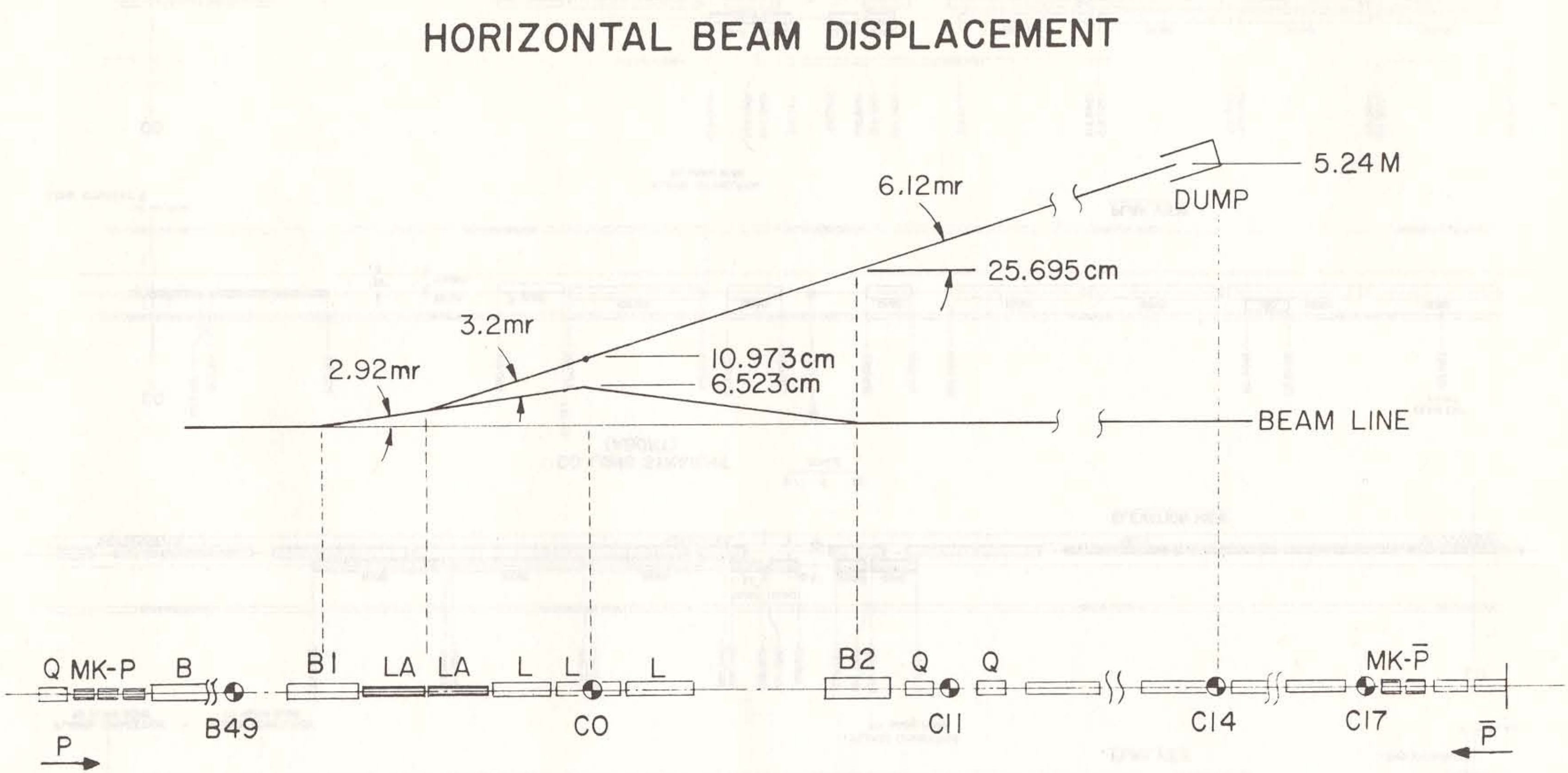

Fig. 11-1. Location of abort-system elements and displacement of aborted beam.

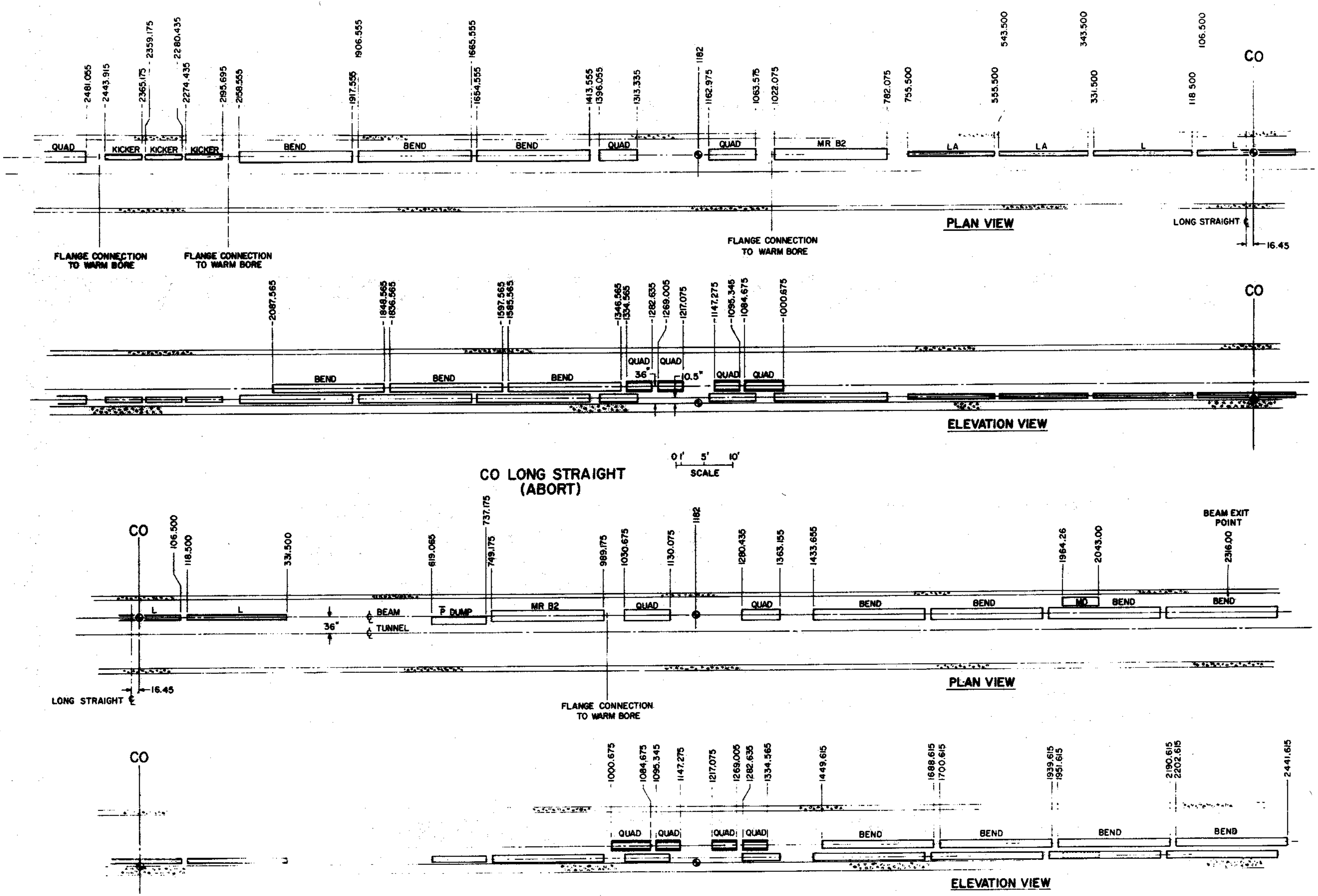

Fig. 11-2. Layout of C0 long straight section.

11.2 The Forward Abort

For the forward proton abort, a 6-m long, 3-kG kicker is placed at the B48 location, 60 m upstream of C0. It deflects the beam downward by 0.54 mrad, resulting in a -20.5 mm displacement and -0.03 mrad slope at the entrance to the long straight section. The closed orbit through the long straight section has a kink of amplitude 6.5cm created by the three horizontally-bending magnets, B1-L-B2. The abort Lambertson magnet, LA, which immediately follows B1, is positioned with its septum centered at -10 mm vertically; LA bends the kicked beam horizontally through +3.2 mrad, providing a +24 cm displacement at the upstream face of B2. Magnet L is a Lambertson which bends only the main beam; in order to increase the vertical separation between the aborted beam and the closed orbit at L (and hence have higher field), LA is rotated by 5° around the beam direction, resulting in a 0.28 mrad downward deflection of the aborted beam. The extracted beam passes through a hole in the return yoke of B2, exits through the wall of the Main-Ring tunnel, and on to a beam dump 120 m downstream of C0. At the dump the extracted beam is 4.4 m from the outside wall of the Main Ring tunnel, as shown in Fig. 11-2. The Lambertson L is 16.2 m in length and will necessarily be made up of three or four modules; a 1-m gap between modules can be arranged in the vicinity of C0 in order to allow for an internal target and utilization of the existing spectrometer room at the Internal Target Area.

The basic parameters of the magnets are listed in Table 11-I. Another magnet, MD, is placed just downstream of magnet B2; the purpose of MD is to sweep the beam vertically in order to increase the effective beam area at the beam dump. MD is a single-turn picture-frame dipole with a half-sine-wave pulse 70 μs long; the field rises from 0 to 4 kG during the 19 μs of beam passage, resulting in an angular sweep of 0.24 mrad.

Table 11-I. Forward Abort Magnet Parameters.

	MK-p	MK-$\overline{p}$	LA	MD	L	B1, B2
Type	1-mil Fe	1-mil Fe	Fe	Fe	Fe	Fe
$\Delta\theta$	0.56 mrad	0.34	3.2	0-0.24	5.84	2.92
Length	3 ×2 m	2 ×2	10.2	2.0	16.2	6.1
Field	3.0 kG	2.8	10.5	5.0	12.0	16.0
Aperture HXV	5 ×5 cm	5 ×5	-	3 × 3	-	10 × 5
Rise Time (95%)	1.5 μs	1.5	Ramped	35	Ramped	Ramped

A cross section of the Abort Lambertson magnet (LA) at the upstream end is shown in Fig. 11-3. In addition to the 10-kG dipole field (at 1000 GeV), it has a gradient of 0.5 kG/cm (horizontally defocusing), which is used to increase the horizontal beam size at the dump. At the center of the long straight section the beam size at 150 GeV is ±3.0 mm. At 1 TeV the main beam is ±1.2 mm, but during slow extraction it has horizontal "wings" extending ±3.4 mm on either side. The abort Lambertson and magnets B1, L, B2 are ramped to track the beam energy.

Without the vertical sweeping action of MD or the focusing action of the abort Lambertson, the 1-TeV beam spot size (2σ) at the beam dump would be ±3.3 mm horizontally by ±2.1 mm vertically. A beam of 2×10^{13} protons with this size would cause physical damage to practically any solid material used in the beam dump. For the most readily available material, aluminum, the beam area should approach 1000 mm^2 to avoid damage. From

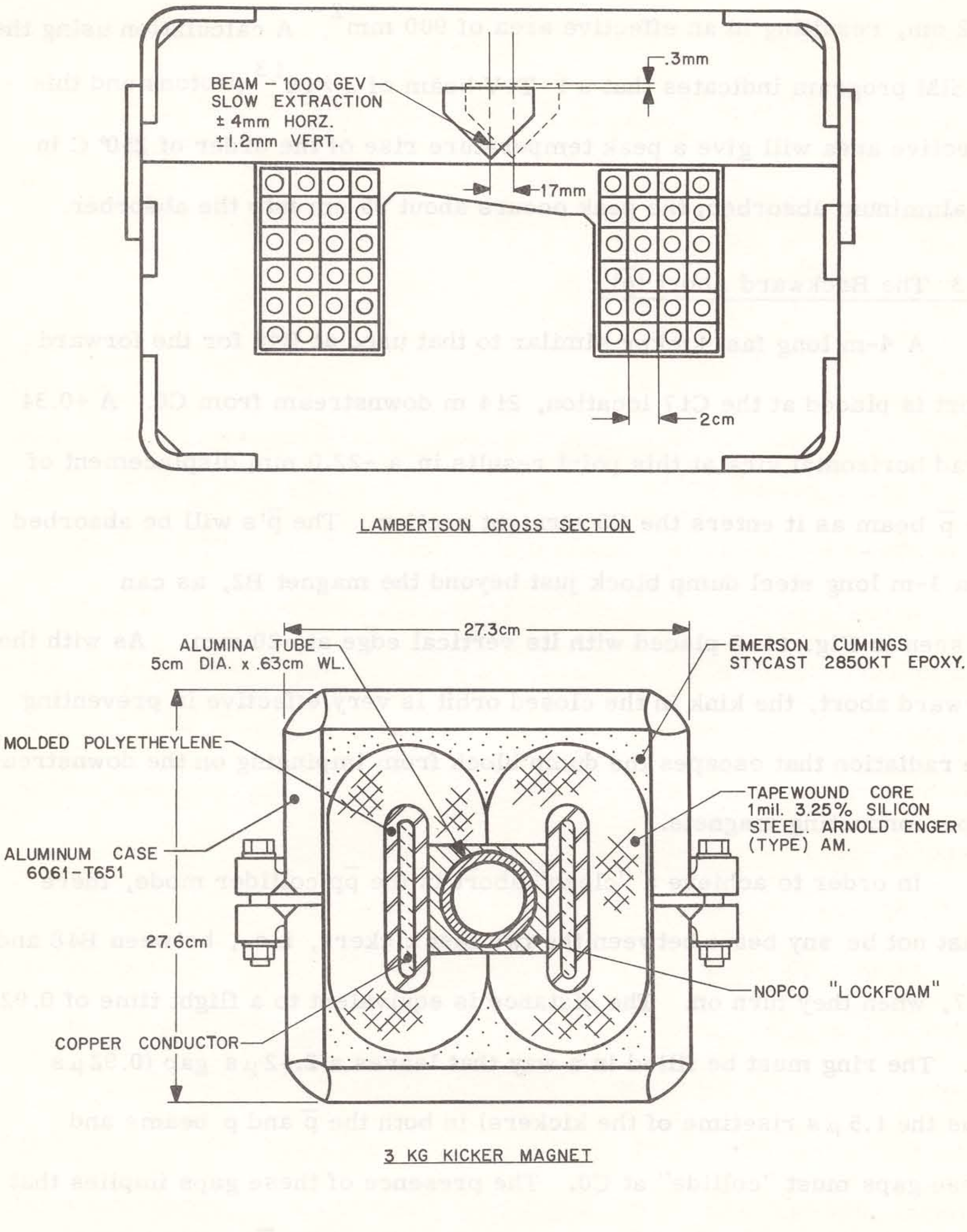

Fig. 11-3. Lambertson and kicker magnets of the abort system.

the lens action of the gradient Lambertson, the horizontal spot size at the dump becomes ±16 mm; the vertical sweep of MD yields a vertical motion of 2 cm, resulting in an effective area of 900 mm^2. A calculation using the CASIM program indicates that a 1-TeV beam of 2×10^{13} protons and this effective area will give a peak temperature rise of the order of 250° C in an aluminum absorber; the peak occurs about 85 cm into the absorber.

11.3 The Backward Abort ($\bar{p}$)

A 4-m long fast kicker similar to that used at B48 for the forward abort is placed at the C17 location, 214 m downstream from C0. A +0.34 mrad horizontal kick at this point results in a -22.0 mm displacement of the $\bar{p}$ beam as it enters the C0 straight section. The $\bar{p}$'s will be absorbed in a 3-m long steel dump block just beyond the magnet B2, as can be seen in Fig. 11-2 placed with its vertical edge at -20 mm. As with the forward abort, the kink in the closed orbit is very effective in preventing the radiation that escapes the dump block from impinging on the downstream superconducting magnets.

In order to achieve a "clean" abort in the $\bar{p}p$ collider mode, there must not be any beam between the two fast kickers, i.e., between B48 and C17, when they turn on. The distance is equivalent to a flight time of 0.92 μs. The ring must be filled in a way that leaves a 2.42 μs gap (0.92 μs plus the 1.5 μs risetime of the kickers) in both the $\bar{p}$ and p beams and these gaps must "collide" at C0. The presence of these gaps implies that up to 77% of the azimuth of the ring can be utilized for $\bar{p}p$ collisions at any given interaction region.

11.4 3-kG Fast Kicker Magnet and Pulsing System

A cross-section view of the kicker magnet is shown in Fig. 11-3. During slow beam extraction, the beam at the B48 location has horizontal wings that extend out to ±17 mm. To accommodate these wings the beam tube through the kicker consists of a 5-cm i. d. ceramic tube, resulting in a 7-cm square gap for the magnet aperture. The magnet core is made with 1-mil tapewound cores of 3.25% silicon steel. Pulse tests carried out on these cores show that a risetime of 1.5 μs (0-95%) is readily obtained. The basic specification for MK-p and MK-$\overline{p}$ are listed in Table 11-I; additional requirements include: 21 μs pulse length, tracking of the ring ramp, and repetition rate of 2 cycles/min. (11 s ramp risetime).

The overall system consists of a charging supply, a pulse line for energy storage, a switch, matched impedance cables, terminating resistors and lumped-element kicker magnets in a series circuit, as shown in Fig. 11-4. In order to achieve the L/R time-constant of 0.5 μs with a reasonable supply voltage (<90 kV), the kickers will be constructed out of 2-m long sections. The pulse line and switch will be located above ground in a service building, approximately 110 m distant from the kicker magnets in the tunnel. Each of the 2 m long kicker modules is fed by a separate 2.5 Ω line. The important design specifications of the subunits of Fig. 11-4 are :

a) Kicker magnet:

$L = \mu_0 \ell = 2.51\ \mu H$ (for $\ell = 2$ m)

$I_{max} = Bd/\mu_0 = 16.7$ ka (for B = 3 kG)

Stored energy = 351 J (≡ E)

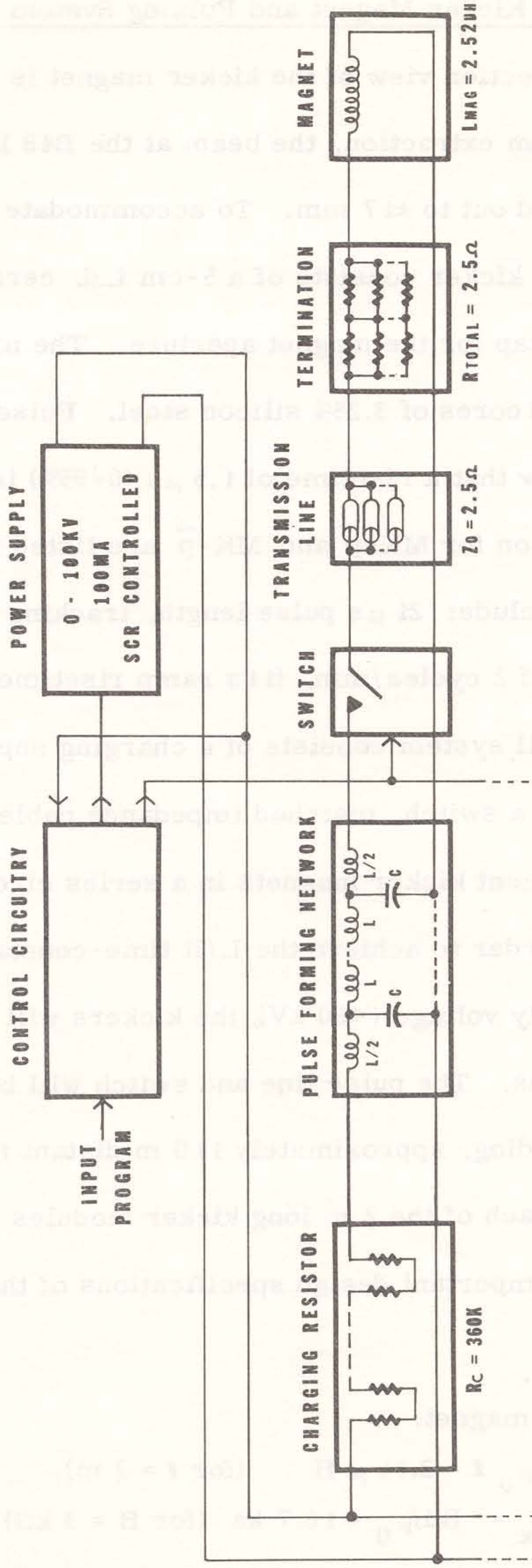

Fig. 11-4. Fast-kicker power supply.

b) Termination resistor:

$Z_0 = L/2\tau = 2.51\ \Omega$

Energy dissipated/pulse = 14.7 kJ

Average power = 489 W (for 2 cycles/min)

To minimize the instantaneous heating of the termination, we have chosen 80-50 Ω ceramic low inductive-power resistors. Each will dissipate 183 J per pulse, giving a temperature rise of 0.92°C after each pulse. If the basic architecture of two resistors in series is adopted, each resistor will have a peak voltage of 20.9 kV and a peak current of 418 A.

c) Transmission line:

Twenty RG220 coax cables (Z_0 = 50Ω) in parallel will be used to transmit the pulse energy to each 2-m magnet in the tunnel.

d) Switch

We are currently planning to use a deuterium-filled ceramic thyratron (English Electric Valve 1192B) as the switch between the transmission line and the pulse-forming network (PFN). The characteristics of the device are:

Required	1192B Rating (crowbar service)
I_{max} = 17 kA	60 kA
I × T = 0.36 A-s	2 A-s
V_{max} = 83.6 kV	90 kV
V_{min} = 12.5 kV	7 kV
dI/dt = 34 ka/μs	100 kA/μs
Rep rate = 2 cycles/min	6 cycles/min

e) Pulse forming network:

$Z_0 = 2.5\ \Omega$, N = 20 sections

$T_s = T/2N = 0.53\ \mu s$

$C_s = T_s/Z_0 = 0.21\ \mu F$; $L_s = Z_0 T_s = 1.33\ \mu H$

Stored energy = ET/τ = 14.7 kJ

f) Power supply and charging resistor:

A single power supply and 3 charging resistors will be used to track the ramp energy. If the maximum voltage on the pulse line corresponding to 1 TeV, is 83.6 kV, the minimum voltage is 12.5 kV, corresponding to 150 GeV. The minimum acceleration time is 11 sec with a period of about 30 sec. Then $\Delta V/\Delta T$ of the pulse line must be 6.46 kV/s. Assuming approximately 10 kV across the charging resistor, the characteristics of the power supply and charging resistor are:

$I_{peak} = 81.4$ mA; $I_{AV} = 35$ mA

$P_{peak} = 7.7$ kW; $P_{AV} = 1.81$ kW

$P_{peak,\ R} = 814$ W; $P_{AV,\ R} = 350$ W

An oil circulation and heat-exchanger system will be used for the supply, charging resistor, PFN, and switch.

11.5 Beam Dump

A possible plan for the beam dump is shown in Fig. 11-5. It is designed to take 3.5×10^{17} protons per year at 1 TeV; at that level it will use up 20% of the Laboratory annual limit for tritium contamination of the ground water. It is intended that this dump will be a common facility to

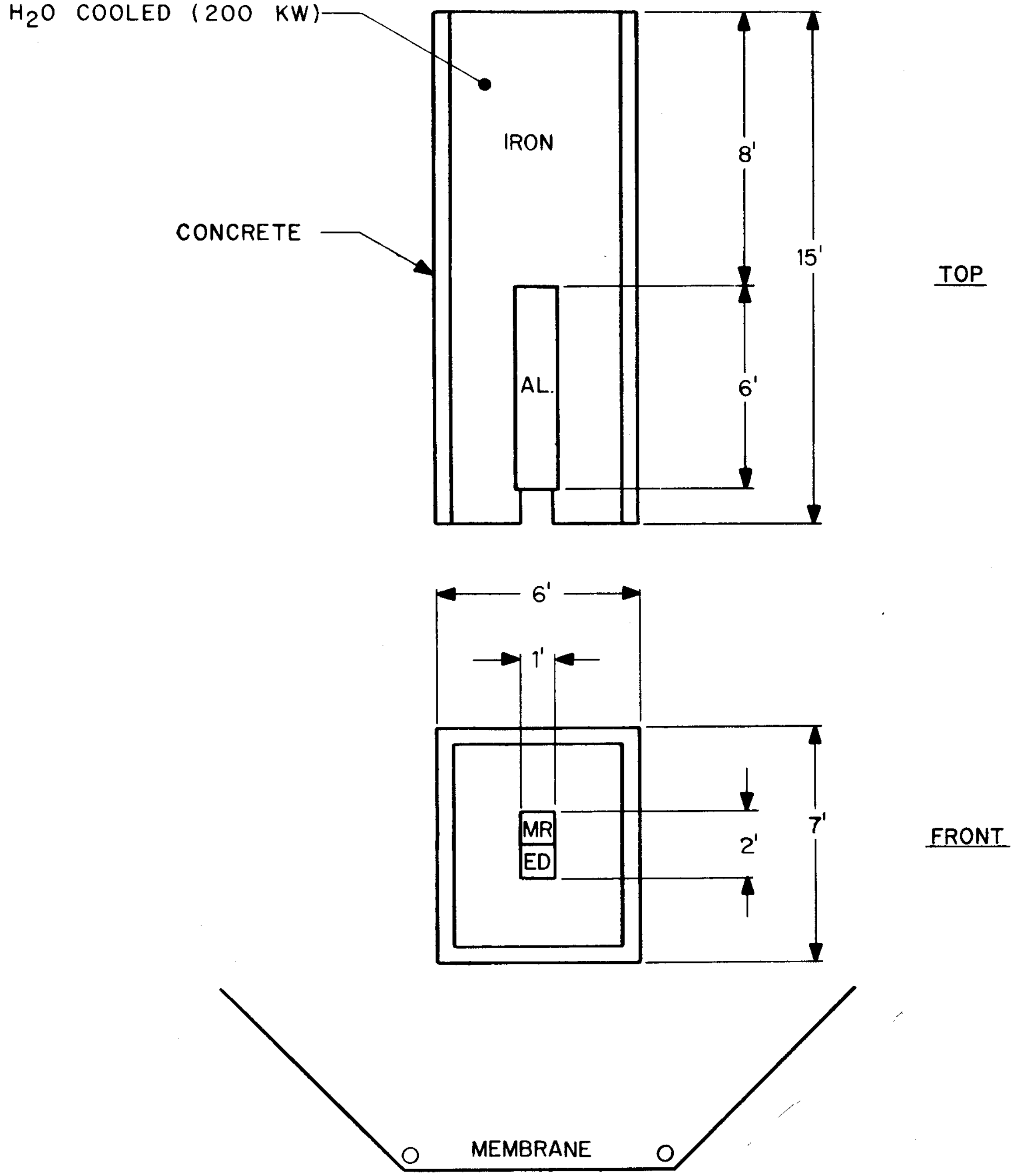

Fig. 11-5. Beam dump.

both the Main Ring and the superconducting ring. The beam impinges on a 6-ft long block of aluminum followed by 8 ft of steel. The membrane shown is a barrier to prevent activation produced above it from passing into the ground water.

Reference

[1]F. Turkot, Energy Doubler Beam Abort System, Fermi National Accelerator Laboratory UPC No. 20, December 7, 1978 (Revised January 1, 1979).