CHAPTER 2

PROTON ACCELERATION AND EXTRACTION FOR ANTIPROTON PRODUCTION

The production of antiprotons is done by bombarding a target with protons that have been accelerated to 120 GeV in the Main Ring. This chapter describes the acceleration of protons in the Main Ring and their subsequent extraction at F17.

2.1 Proton Acceleration

The accumulation cycle begins by accelerating a single Booster batch of protons in the Main Ring to 120 GeV with the existing rf system. This Booster batch consists of a string of 82 bunches spaced 5.6 m apart; its total length is 457 m. A single batch fills less than one-thirteenth of the Main Ring circumference. The Booster intensity record for a single batch is 3.4×10^{12}. For the purpose of this report, it is assumed that an intensity 2.0×10^{12} protons per Booster batch will be standard operating intensity for $\bar{p}$ production. The minimum time needed to accelerate a single batch to 120 GeV in the Main Ring can be reduced to 1.87 seconds. A flat-top of 0.13 sec is added to provide time for the rf beam manipulation before extraction. The cycle time is 2 seconds. The major beam properties are given in Table 2-I.

TABLE 2-I MAIN RING BEAM PARAMETERS

Proton Beam Kinetic Energy @ Extraction	120 GeV
Relativistic Factors: β	0.99997
γ	128.9318
$B\rho$, magnetic rigidity	4035.506 kG-m
Momentum, p	120.9347 GeV/c
Number of Booster batches accelerated	1
Number of Proton Bunches	82
Total number of protons per Batch	2.0×10^{12}
Main Ring Cycle Time	2.0 sec
Betatron Emittance, 95% of beam, (H and V)	0.2π mm-mrad
Longitudinal Emittance, 95% of beam at 120 GeV	0.3 eV-sec
RF harmonic number (h)	1113
RF Frequency @ 120 GeV	53.1035 Mhz
Revolution Period @ 120 GeV	20.96 μsec
Booster Batch Time Length	1.56 μsec
Transition Energy (γ_t)	18.75
Betatron tune number (H and V)	19.4
$\eta = \gamma^{-2} - \gamma_t^{-2}$	-0.0028
Maximum RF voltage	4.0 MV
Average Radius	1000 m

A reasonable estimate for the normalized betatron emittance, based on measurements,[1] is 24π mm-mrad. This value includes 95% of the beam. If $\sigma_{H,V}$ denotes the rms beam size and $\beta_{H,V}$ the lattice amplitude function, the emittance can be expressed in terms of these quantities as

$$\varepsilon_{H,V} = 6\pi \frac{\sigma^2_{H,V}}{\beta_{H,V}} .$$

The longitudinal phase-space area S of individual bunches in a Booster batch has been measured to be 0.3 eV-sec or less.[2] If the particle distribution is biGaussian in these variables, this value includes 95% of the beam. There is reason to believe this number can be reduced to <0.2 eV-sec in the future when improvements are made to the Main Ring and the Booster rf systems.

For energies well above the transition energy, a bunch area S half as large as the bucket area, and a bunch shape matched to the rf bucket, the rms bunch length σ_e and rms momentum spread σ_p/p are

$$\sigma_e = (142\text{cm})\sqrt{\frac{S}{\sqrt{VE}}} \qquad \sigma_p/p = (0.0112)\sqrt{\frac{S}{\sqrt{E^3/V}}} .$$

The bunch area can be expressed in terms of these quantities as

$$S = 6\pi\beta E \frac{\sigma_e}{c} \frac{\sigma_p}{p} .$$

The bucket area of a stationary bucket B and the phase-oscillation period T_s are respectively

$$B = (0.34 \text{ eV-sec}) \sqrt{VE} \qquad T_s = (1\text{msec}) \sqrt{E/V} .$$

In all these equations E is in GeV, V in MV and S in eV-sec.

For a fixed antiproton momentum spread, the bunch area of the antiprotons is minimized by making the time spread of the extracted proton bunches as narrow as possible. At the end of acceleration when the rf voltage is 4 MV the relevant beam parameters are T_s = 5.6 msec, σ_e = 16 cm, $\sigma_p/p = 2.4 \times 10^{-4}$ for a longitudinal emittance of 0.3 eV-sec.

The rf voltage is quickly turned off from its normal flattop value of 1 MV per turn for 2.9 msec (ε_{ℓ} = 0.3 eV-sec value) so that the bunch shears to the extent required for a subsequent rotation. The rf voltage is then turned on quickly to rotate the sheared distribution. Both the turning off and the turning on are accomplished in about 40 μsec. After 1.6 msec, the distribution has rotated to its narrowest projection. At that moment the phase-oscillation period T_s = 5.6 msec, σ_e = 6.8 cm, and $\sigma_p/p = 6.8 \times 10^{-4}$. After these operations have been completed, a momentum spread of 0.3% contains 95% of the beam. The bunch-narrowing process is illustrated in Figure 2-1.

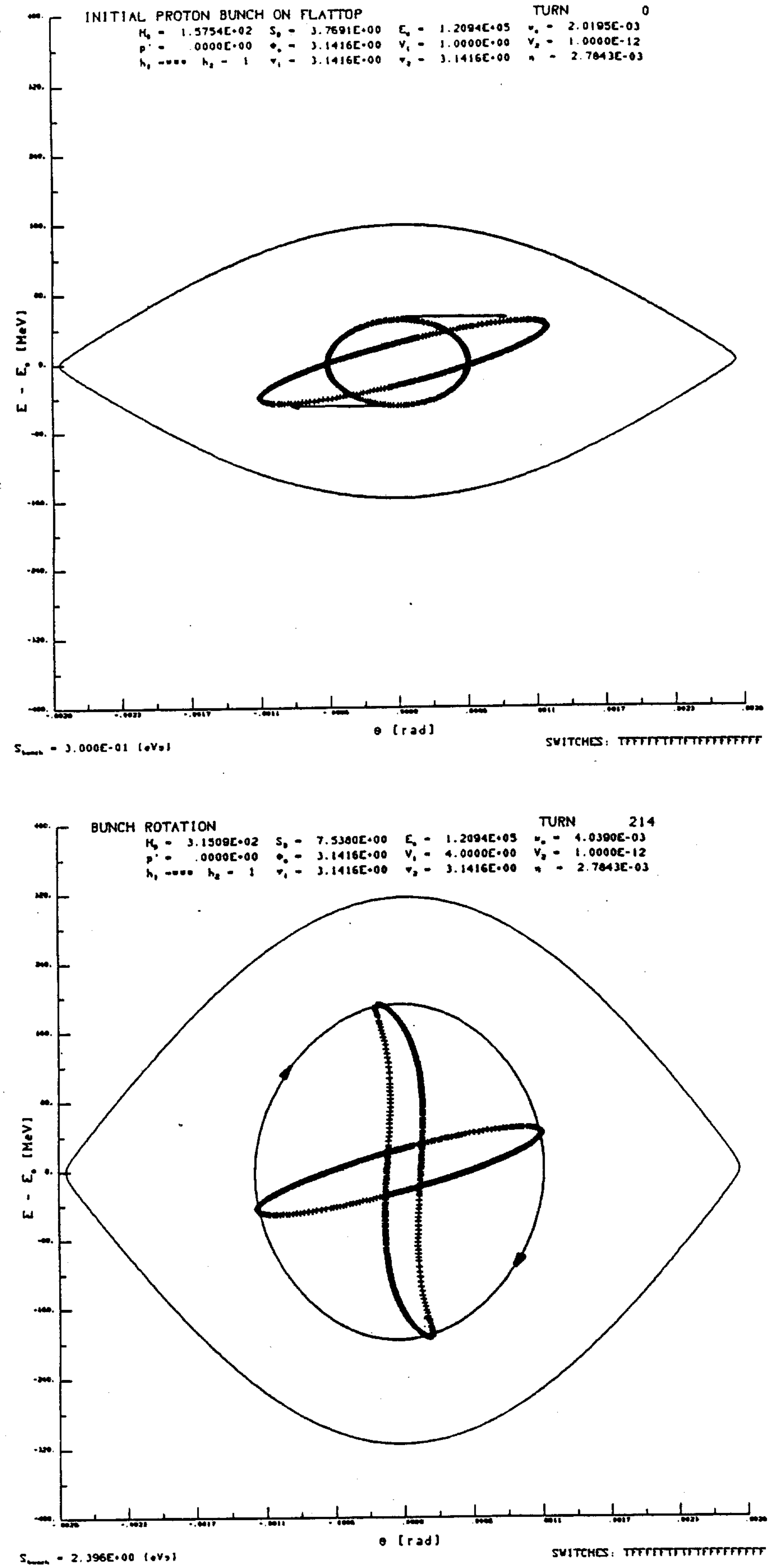
The results of recent bunch-narrowing experiments in the Main Ring at 120 GeV, March 1982,[2] are shown in Fig. 2-2. In these experiments the maximum rf voltage was limited to 3.6 MV. Shorter bunches can be obtained by using the full available 4 MV.

Measurements made in the Main Ring[3] have shown that the available momentum aperture is ±0.27% for 90% beam transmission at 120 GeV with extraction equipment for the Tevatron in place. The loss of beam due to the 0.4% momentum spread is expected to be small, since very little of the beam will extend into the bad-field region of the aperture. As soon as the bunch rotation is complete, all 82 bunches are ejected at F17 into the 120-GeV transport line.

2.2 Extraction at F17

The dynamics of the process of proton extraction for $\bar{p}$ production is relatively straightforward. The proton energy at extraction will be in the range of 120 to 150 GeV (although for all the calculations discussed below, 149 GeV has been assumed.) A new kicker at E17 is energized to produce coherent betatron oscillations, which result in a beam displacement of roughly -42 mm at F17.

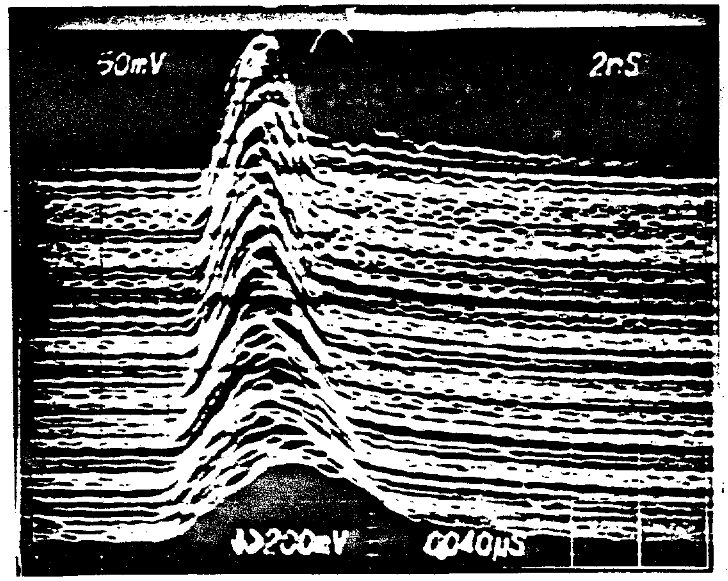
The kicker magnet will be a copy of the present 75-in. Main Ring abort kicker, which is a lumped inductance system with a tape-wound core. The necessary kick angle of approximately 450 μrad is expected to require approximately 5 kA. The half-sine-wave current pulse will have a risetime of approximately 15 μsec and a flat-top uniformity of ±.2% during the beam pulse. The kicker action is sufficient to cross the magnetic septum of a Lambertson placed at F17. Prior to extraction, the closed orbit between D38 and F14 is modified by energizing small dipoles at these locations (an existing magnet at D38 and a new one at F14.) The resulting orbit bumps are roughly out of phase with the kicker coherent oscillation, and serve to minimize excursions from the nominal Main Ring center until F17. Additional steering of the circulating beam horizontal position (of up to 13 mm) at F17 is provided by the F14 dipole and another new one at F19. The F14-F19 bump could be used to keep the accelerated beam away from the septum during acceleration, if necessary, and turned off as the D38-F14 pair is energized to prepare for extraction.



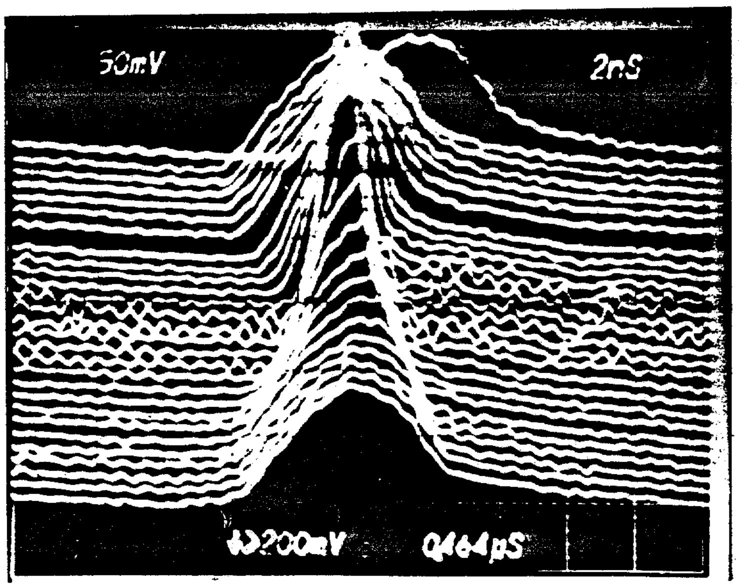
a) Outline of a Main Ring bunch of 0.3 eV-sec phase-space area matched to a bucket produced by 1 mV of rf at 120 GeV and the outline of the same bunch after 2.9 ms (140 turns) of drift with the rf off.

b) Rotation of the drifted bunch (a) in a bucket produced by 4 mV over a 1.6 msec interval.

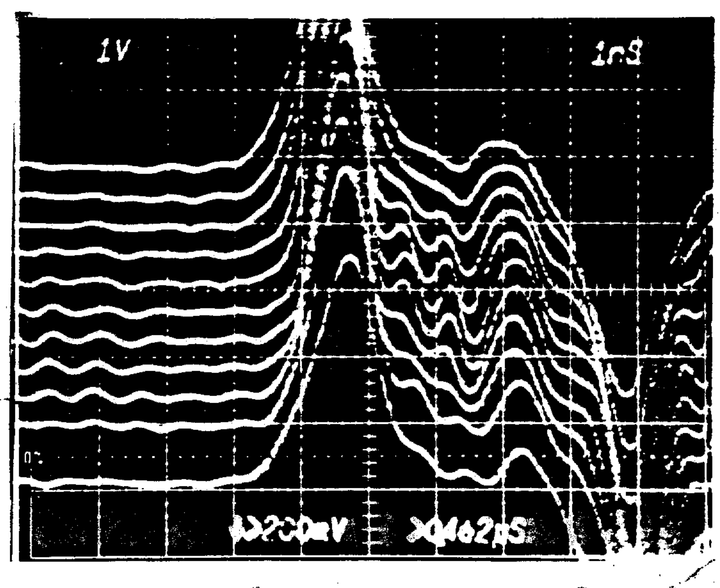
Figure 2-1 Bunch narrowing for $\bar{p}$ production.



a) Bunch broadening. Time progresses downward, and total debunching time is 100 ms. The final bunch length is about 9 ns.



b) Rotation of mismatched bunch following sudden increase of the RF voltage to 1 MV. Time progresses downward, and traces are separated by about 100 ms. The topmost trace results from a mistrigger.



c) Bunch lengths near the time of narrowest bunches. Traces are taken at the beam rotation frequency, every 20.9 μs. The bunch pickup is a broadband transmission line, so inverted reflections from the downstream end of the pickup also appear In this experiment the maximum RF voltag was 3.6 MV. Narrower bunches would be obtained with nominal 4 MV. A bunch wit a 95% full time width of 1 ns has a leng of 7.5 cm rms.

Figure 2-2 Debunching and Bunch Rotation.
Time base is 20 ms per major division.

The extraction channel is formed by two 162-in. Lambertsons, followed by two 118.4-in. C-magnets. The extraction magnets kick the beam vertically up by 32.6 mrad, which is sufficient to allow the extracted beam to pass above the next Main Ring dipole. The total vertical distance above Main Ring center at the end of the extraction channel is 9.7 in. The Lambertsons operate at approximately 10.6 kG and the C-magnets at 12.7 kG. The extraction magnets will be excited in series by a resonant LC pulser resulting in one cycle of a sine-wave of period 70 msec and peak amplitude 3000 A.

To make room for the system, the Main Ring B2's at slots F17-4 and F17-5 are replaced with a modified B2, which has twice the number of turns, and which is run in series with the rest of the Main Ring. Additional components of the system are a horizontal trim magnet located 140 in. downstream from the second C-magnet and a trim magnet located after the new B2. The first trim is intended to compensate for the difference in angle at F17 between the extracted and injected beams. The second trim compensates for small field differences between the modified B2 and the original standard B2's. The layout of the system is shown in Fig. 2-3.

The following calculations have been done for a momentum of 150 GeV/c, using a normalized emittance of 25 π mm-mrad, and a momentum spread of ±0.2%.

Figure 2-4 shows the closed orbit with the D38, F14 pair; Figure 2-5 shows the D38, F14 bumps plus the extraction orbit produced by adding the E17 kicker.

Figure 2-6 shows the region near F17 in detail, indicating both the circulating and kicked beam envelopes. Note that the extracted beam explores nearly the full inner limit of the physical aperture of the dipoles and quad upstream of F17. The residual angle of 0.8 mrad of the extracted beam at the entrance to the first Lambertson is taken out by rolling the magnet by 5.2 deg (see dotted line.)

Figures 2-7, 2-8 and 2-9 show the beam spot(s) at the F17-1 quad, the Lambertsons and the C-magnets; both the circulating and the extracted beams are shown. In the figures, the dotted line indicates the beam spot when the F14-F19 pair is energized to its nominal value (13 mm offset.) In Fig. 2-8 the beam in the extraction channel is shown at the entrance of the first and exit of the second Lambertson. Fig. 2-9, shows the beam envelopes at the entrance and exit to the C-magnets, as well as the circulating beam. The C-magnets are pitched at roughly 1.2 deg vertically, so that the beam exits near the middle of the downstream aperture.

The residual field in the field-free region of the Lambertson is estimated to be 30 G at 150 GeV. The fields below the C-magnet, in the region of the circulating beam, are roughly a few tenths of a Gauss at 8 GeV, rising to less than 80 G at 150 GeV. It is planned to further suppress these by using a magnetically shielded beam pipe in this area.

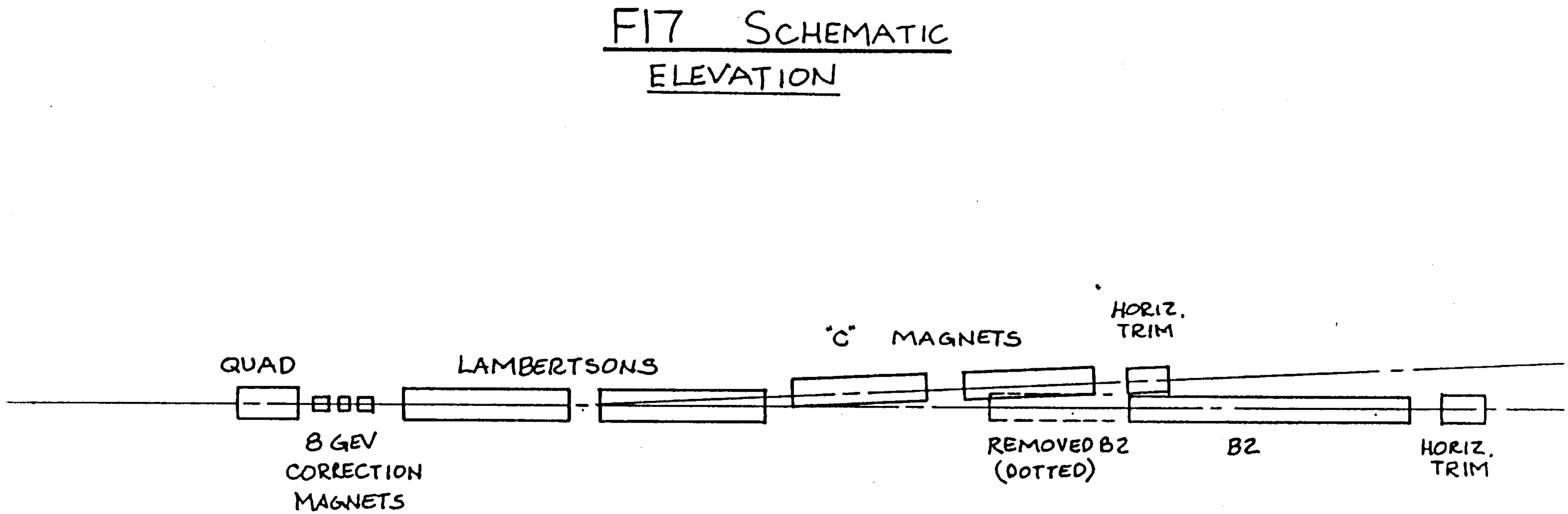

F17 SCHEMATIC
ELEVATION
QUAD
8 GEV
CORRECTION
MAGNETS
LAMBERTSONS
"C" MAGNETS
HORIZ.
TRIM
REMOVED B2
(DOTTED)
B2
HORIZ.
TRIM

Figure 2-3

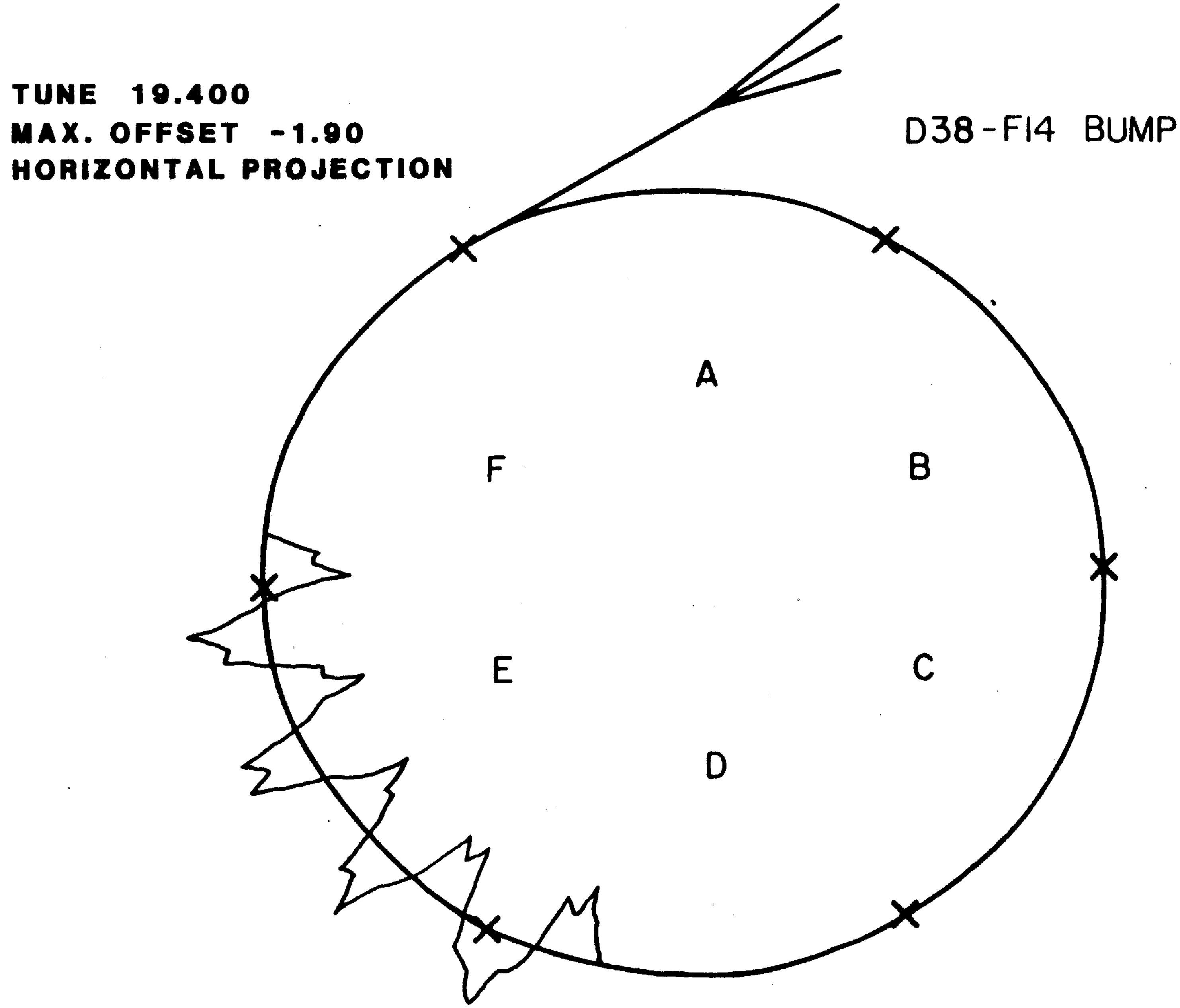

TUNE 19.400
MAX. OFFSET -1.90
HORIZONTAL PROJECTION
D38-F14 BUMP
A
B
C
D
E
F

Figure 2-4

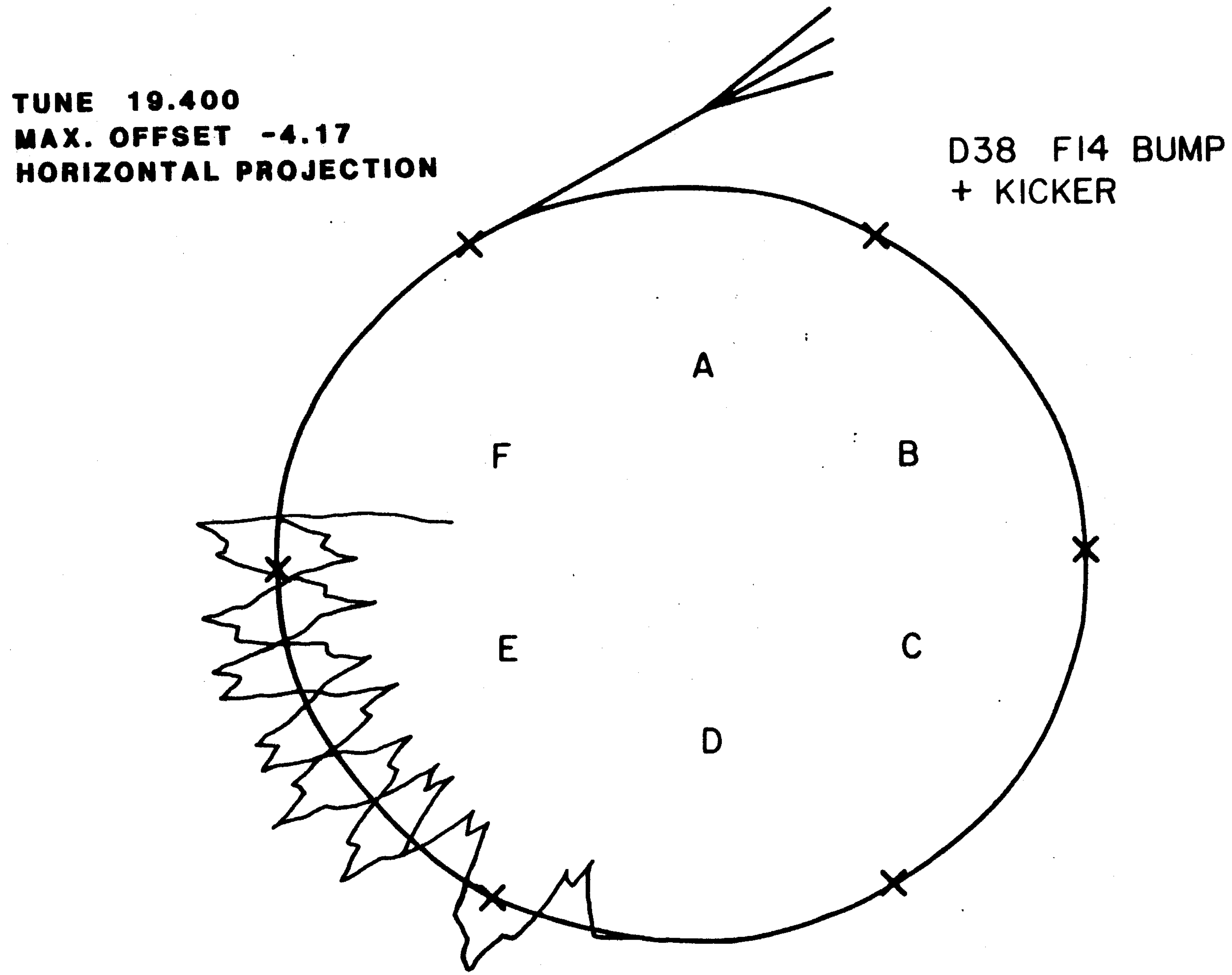
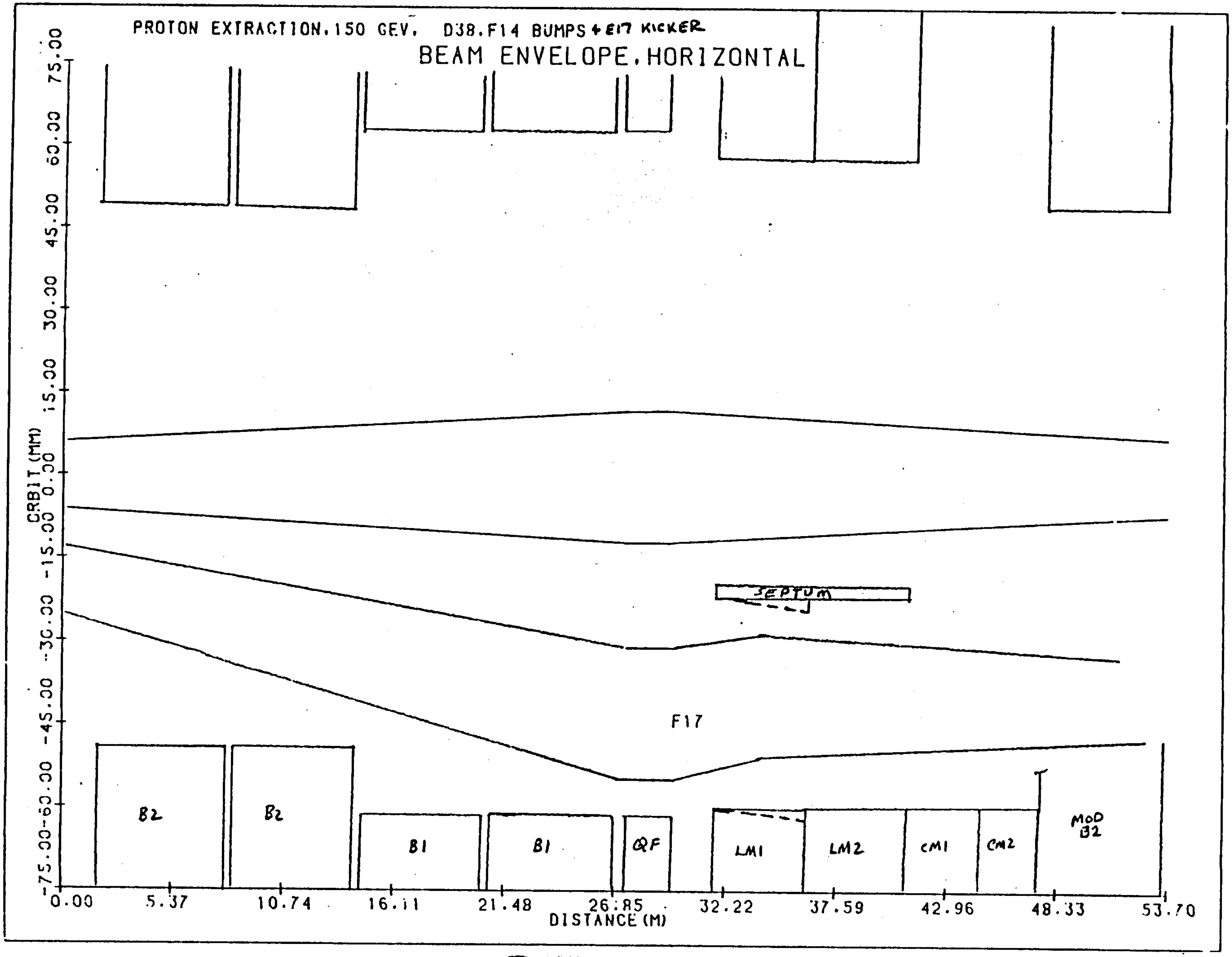

TUNE 19.400
MAX. OFFSET -4.17
HORIZONTAL PROJECTION
D38 F14 BUMP
+ KICKER
A
B
C
D
E
F

Figure 2-5


PROTON EXTRACTION, 150 GEV. D38, F14 BUMPS + E17 KICKER
BEAM ENVELOPE, HORIZONTAL
ORBIT (MM)
75.00
60.00
45.00
30.00
15.00
0.00
-15.00
-30.00
-45.00
-60.00
-75.00
SEPTUM
F17
B2
B2
B1
B1
QF
LM1
LM2
CM1
CM2
MOD B2
0.00
5.37
10.74
16.11
21.48
26.85
32.22
37.59
42.96
48.33
53.70
DISTANCE (M)

Fi

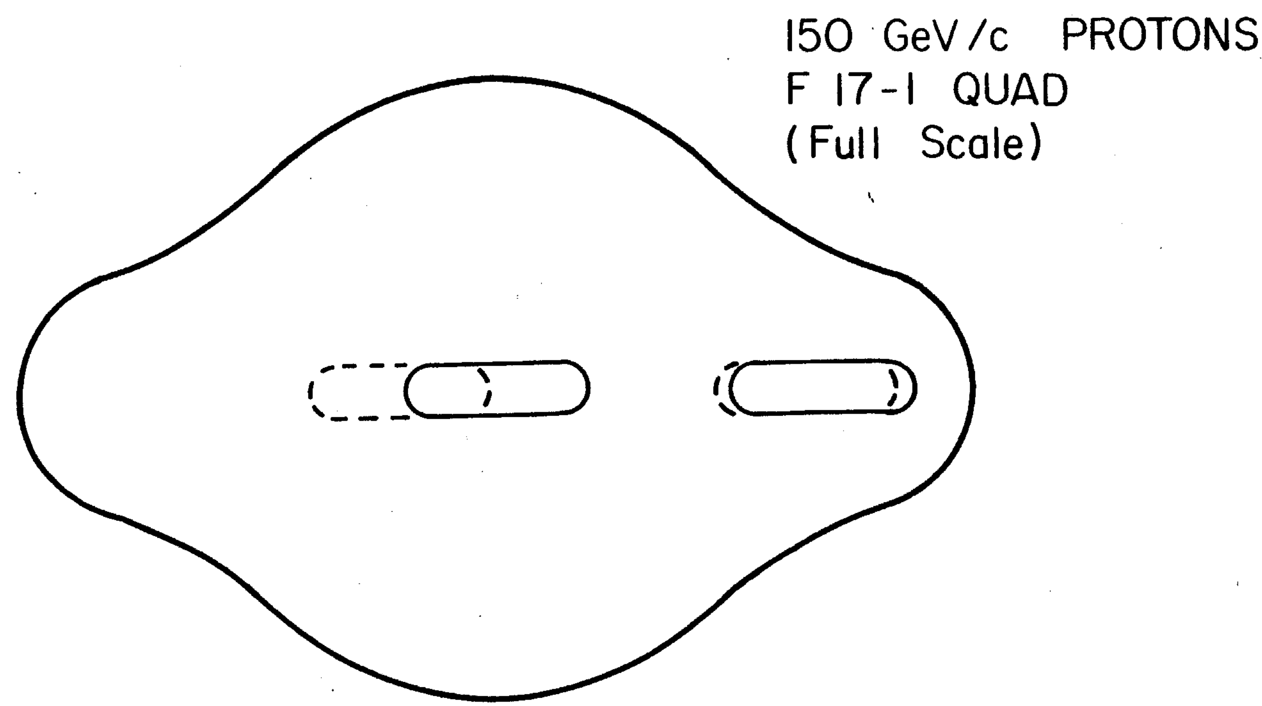


Figure 2-7

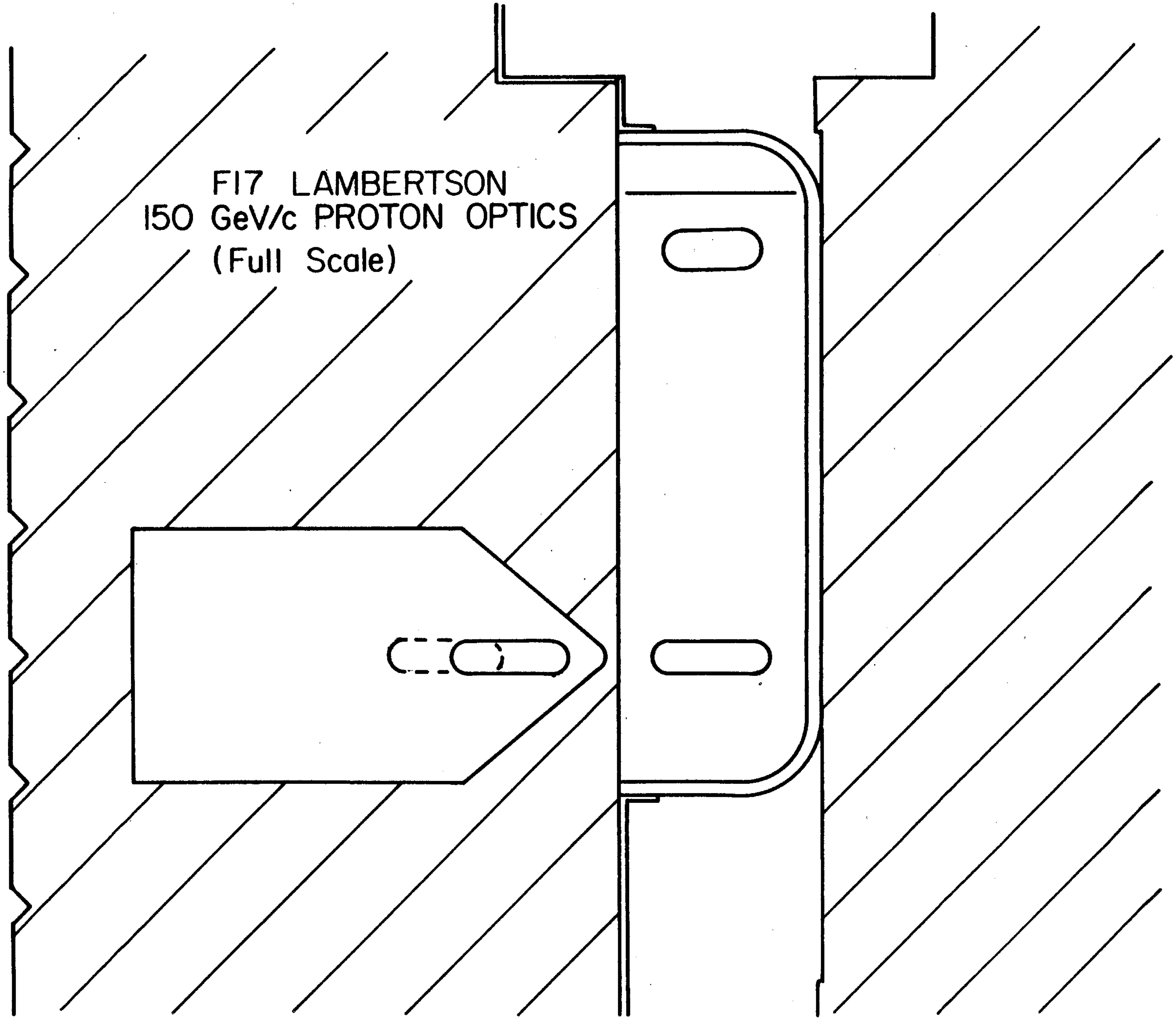


Figure 2-8

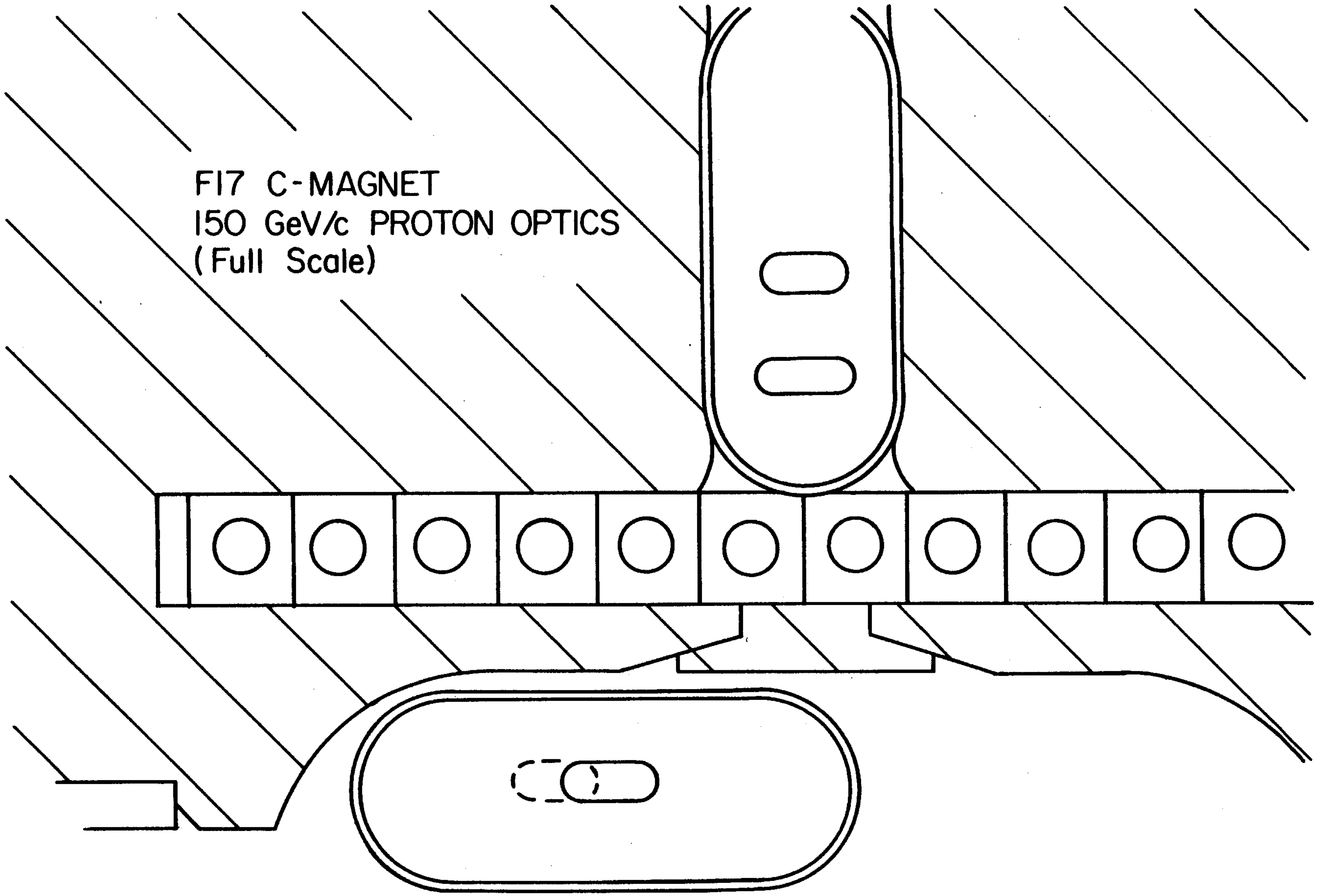


Figure 2-9

Transport of the 120-GeV protons to the target is discussed in Sec. 11.1.

References

1. C. Moore et al., Fermilab EXP Note 101, February 1980 (unpublished).

2. J. Griffin (unpublished).

3. J. Griffin, Fermilab Report, 7, July 1982.