10. INJECTION

10.1 Introduction

The beam-transfer system from the Main Ring to the superconducting ring for both normal and reverse directions is essentially the same as that reported previously.[1] In the vertical plane, two Lambertson magnets form a dogleg to lower the Main-Ring beam by 25.5 in. In the horizontal plane, one fast kicker is used to extract the beam from the Main Ring and another to inject it into the new ring. In addition to these, two bump magnets in the Main Ring are used to adjust the closed orbit. Similar adjustments of the superconducting-ring closed orbit during beam transfer will be made by the regular steering elements built into quadrupoles. Space is available between the rings to install one small quadrupole common to both directions, useful for fine matching of beam shapes. Steering dipoles of modest size may also be placed there if needed. Specifications for all these magnets are not terribly difficult, but some developmental work may be required to improve the fast-kicker system.

The design presented here takes into account the somewhat complicated relative geometry of the two rings.[2] In the long straight section, the beam in the new ring is inside the Main Ring, but crosses it near the downstream end. For beam transfer, which is planned to be at 150 GeV/c, the Main-Ring beam must have a momentum offset of +0.25% for synchronous transfer and this moves the Main-Ring beam even farther out. It has been decided that the beam transfer will be done in long straight section E for both directions. One advantage of this scheme compared with the previous design, in which two long straight sections were used, is that some magnets can be shared by the normal and reverse beam transfers. At the same time, the essential features of the design are not affected much by this choice.

There are a number of important factors dominating the design of the system: (i) beam characteristics, (ii) Main-Ring aperture at 8-GeV injection, (iii) superconducting-ring aperture for circulating and for single-passage beams, (iv) maximum fields of septum magnets, (v) maximum integrated field, rise and fall times, and field ripple of fast kickers. Depending on how one factor is weighed relative to others, many variations of the design are possible and, as more information becomes available, the present design will probably be modified. What is presented here is an example demonstrating that there are no fundamental difficulties in beam transfer in either direction.

10.2 Beam Characteristics

10.2.1 Injection energy. The beam line is 25.5 in. below the Main-Ring beam line and the beam must be brought down in less than 50 m, the length of a long straight section. The upper limit of the beam momentum is then dictated by the bend fields achievable in septum magnets and the strengths of fast kickers. The lower limit is determined by the field quality of the superconducting magnets. Measurements indicate poor field quality at an excitation current of 200 A (45 GeV/c). Even at 500 A (113 GeV), the relative sextupole component of dipole magnets is 50% larger than at higher currents (see Fig. 3-11). Beyond 1,000 A (226 GeV/c), the field quality is essentially independent of the excitation currents. It is therefore assumed here that the transfer momentum is 150 GeV/c, which corresponds to 660 A. More careful design of septum magnets and kickers may show a possibility of using higher momentum values. Below 1,000 A, the magnetic field is modified by hysteretic magnetization that is produced by persistent current in superconducting filaments. The resulting field distortion in dipoles is mostly sextupole field and its magnitude depends strongly on the ramp history. In operation, the ramp current should be cycled to 500 A or lower to set the magnet fields on the proper side of the hysteresis loop. The possibility of introducing harmonic corrections for half-integer and third-integer resonances during beam transfer should not be excluded in the overall design.

<u>10.2.2 Longitudinal emittance.</u> A measurement[3] at 125 GeV/c gives 0.37 eV-s (90% of the beam, bunch spreader off) when the intensity is 2×10^{13}. There are reasons to believe that this value could be reduced by improvements in the Main-Ring injection phase-lock and in transition crossing. The value used here is 0.25 eV-s. At approximately 1 MV/turn in the Main Ring, the beam injected into the new ring is expected to have a momentum spread of $\pm0.25\times10^{-3}$. The contribution to beam size arising from dispersion is then less than ±1 mm in the long straight section. The beam will be transferred into stationary rf buckets with constant magnetic field, so there will be no mismatch and the momentum spread of the beam may be reduced by reducing the Main-Ring rf voltage. There may be a limit to the minimum value of the momentum spread one can achieve; too-small values might induce microwave instabilities. If the beam were transferred to accelerating rf buckets, say 50 GeV/s, with a synchronous phase = 133°, there would be a mismatch and the momentum spread of the circulating

beam would increase to $\pm 0.33 \times 10^{-3}$ or more, depending on the Main-Ring rf voltage at the time of transfer. Any error in the phasing would contribute to a further increase in the spread and in the emittance. It is desirable to limit this error to within $\pm 5°$.

10.2.3 Transverse emittance. For single-turn injection of H^+ to the Booster, the emittance measured in the 8-GeV transport line is $(1.0$ to $1.2)\pi$ mm-mr. If there are no dilutions caused by mismatching or nonlinear fields, the emittance at 150 GeV/c will be 0.07π mm-mr. As a more realistic value, 0.15π mm-mr (95%) is assumed for the design. There are very few data available for multi-turn H^- injection into the Booster, but it is generally believed that the emittance is the same or only slightly larger.

10.3 Apertures

The radial offset of the ring relative to the Main Ring in the long straight section is shown schematically in Fig. 10-1. In order to make pp collisions of $(150$ to 200 $\mathrm{GeV/c})_{MR} \times (1{,}000$ GeV/c) possible, the path length is designed to be longer by a factor 7.0×10^{-6} compared with the Main Ring. As a consequence, the Main-Ring beam must have a momentum offset of +0.25% during beam transfer if the beam is to be injected with zero momentum offset in the superconducting ring. The septum magnets should not be too close to the beam axes, although how much space is really needed is not well defined. Larger space would certainly make operation easier. In the present design, the kicker in the Main Ring for normal transfer is placed at station 48 immediately upstream of the septum magnet in order to prevent a large beam excursion at that point. In the new ring the falloff of the design

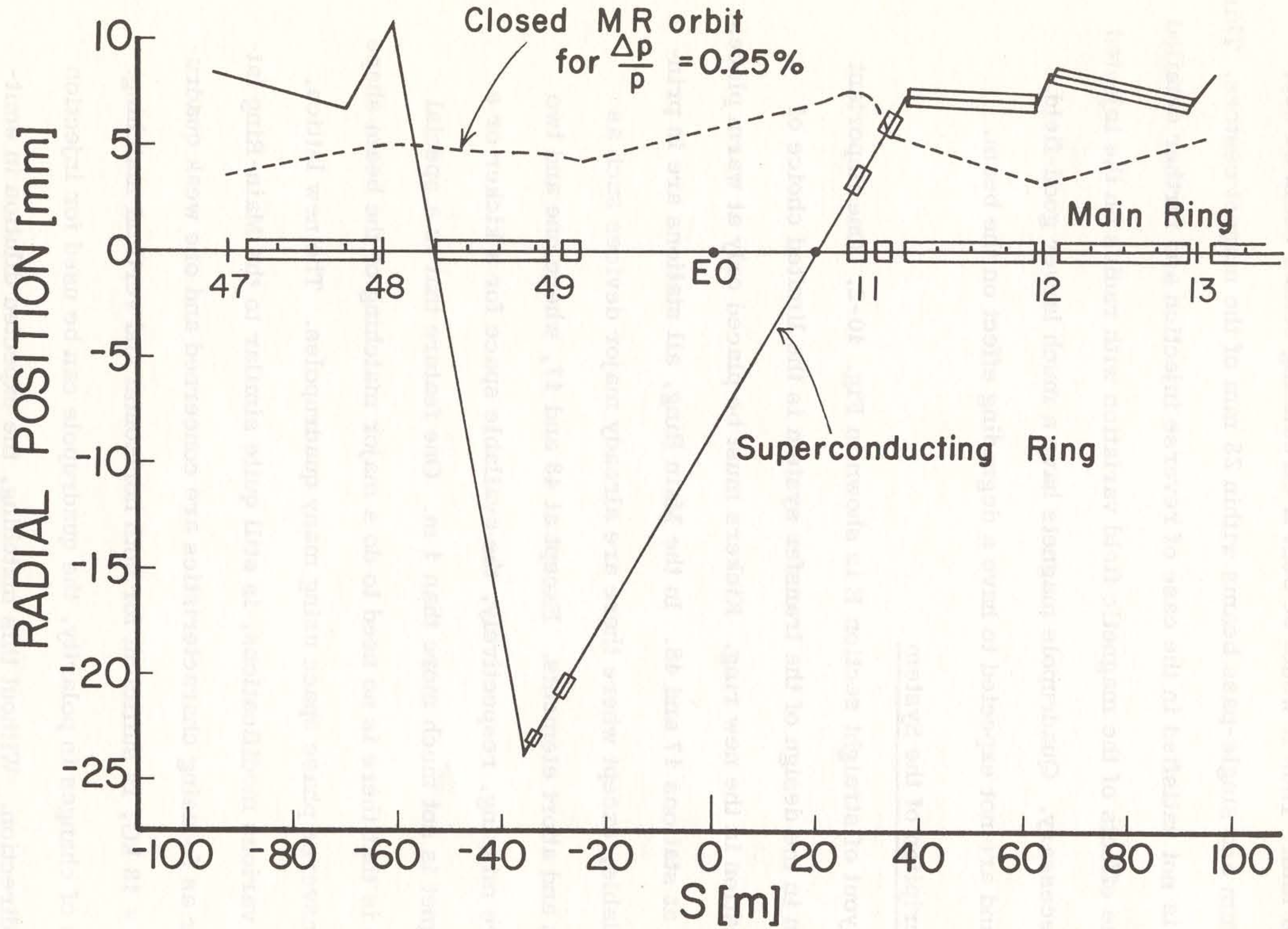

Fig. 10-1. Radial positions of the off-momentum closed MR orbit and the Superconducting Ring relative to the Main Ring.

field in the bending magnets starts at ±20 mm and has dropped to a $\Delta B/B$ of 10^{-3} at ±28 mm. Thus it would be best if circulating beams could be kept within 20 mm and single-pass beams within 28 mm of the magnet centers. This criterion is not satisfied in the case of reverse injection and further detailed study of the effects of the magnetic-field variation with radius on the injected beam is necessary. Quadrupole magnets have a much larger good-field aperture and are not expected to have a degrading effect on the beam.

10.4 Description of the System

A layout of straight section E is shown in Fig. 10-2. One important restriction in the design of the transfer system is the limited choice of kicker location in the new ring. Kickers must be placed only at warm places, which are at stations 17 and 48. In the Main Ring, all stations are in principle available, except where there are already major devices such as extraction and abort elements. Except at 48 and 17, where one and two dipoles are missing, respectively, the available space for a kicker or a bump magnet is not much more than 1 m. One feature that is a special advantage is that there is no need to do a major matching of the beam shape in the transverse phase space using many quadrupoles. The new lattice, even with various modifications, is still quite similar to the Main-Ring lattice as far as focusing characteristics are concerned and one weak quadrupole, $B'\ell$ = 18 kG, is sufficient for both horizontal and vertical matching. By means of changes in polarity, the quadrupole can be used for injection in either direction. Without this matching, the expected dilution in emittance is approximately 30%. The location of this matching quadrupole is shown in Fig. 10-3.

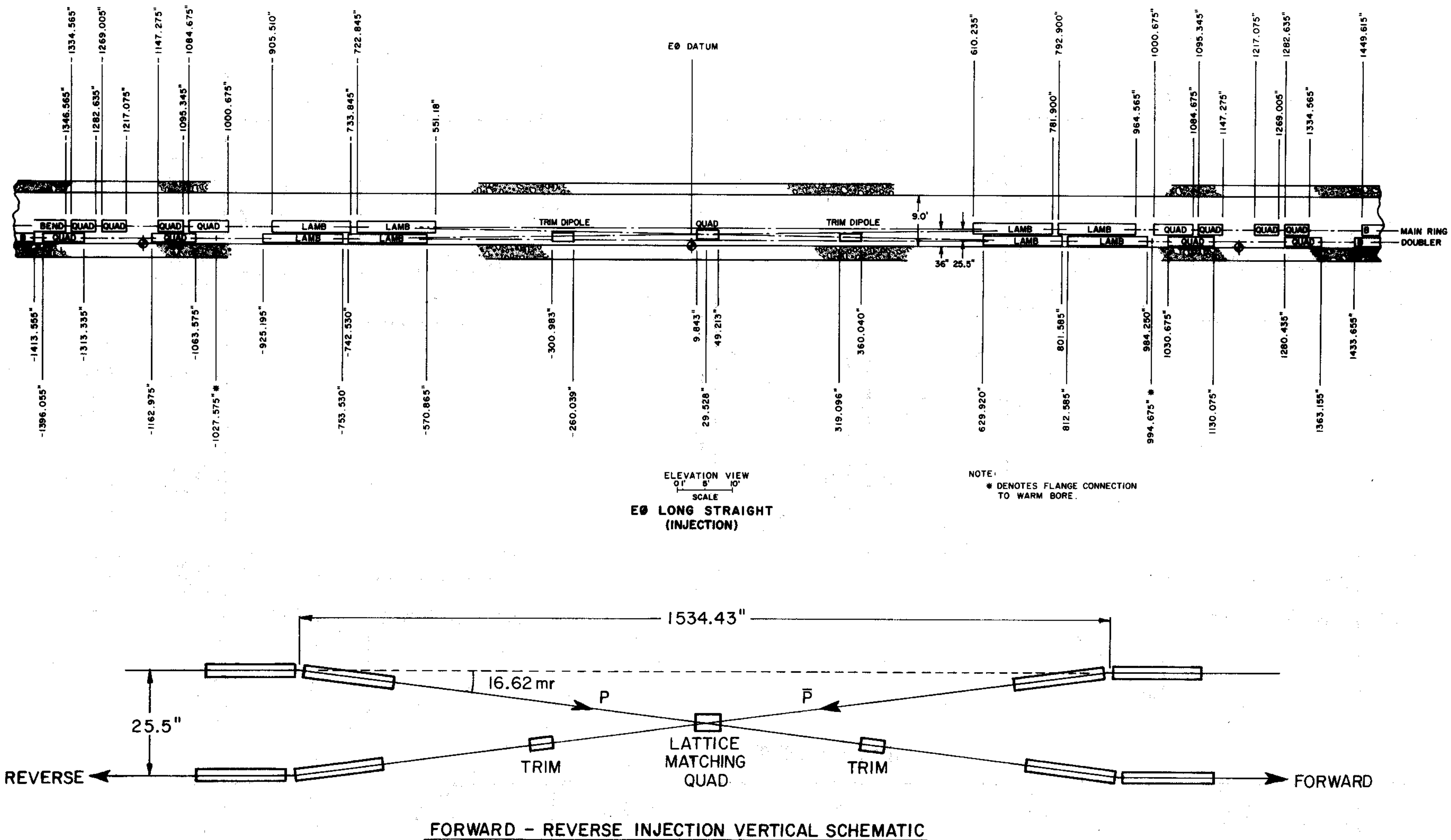

Fig. 10-2. Layout of E0 long straight section.

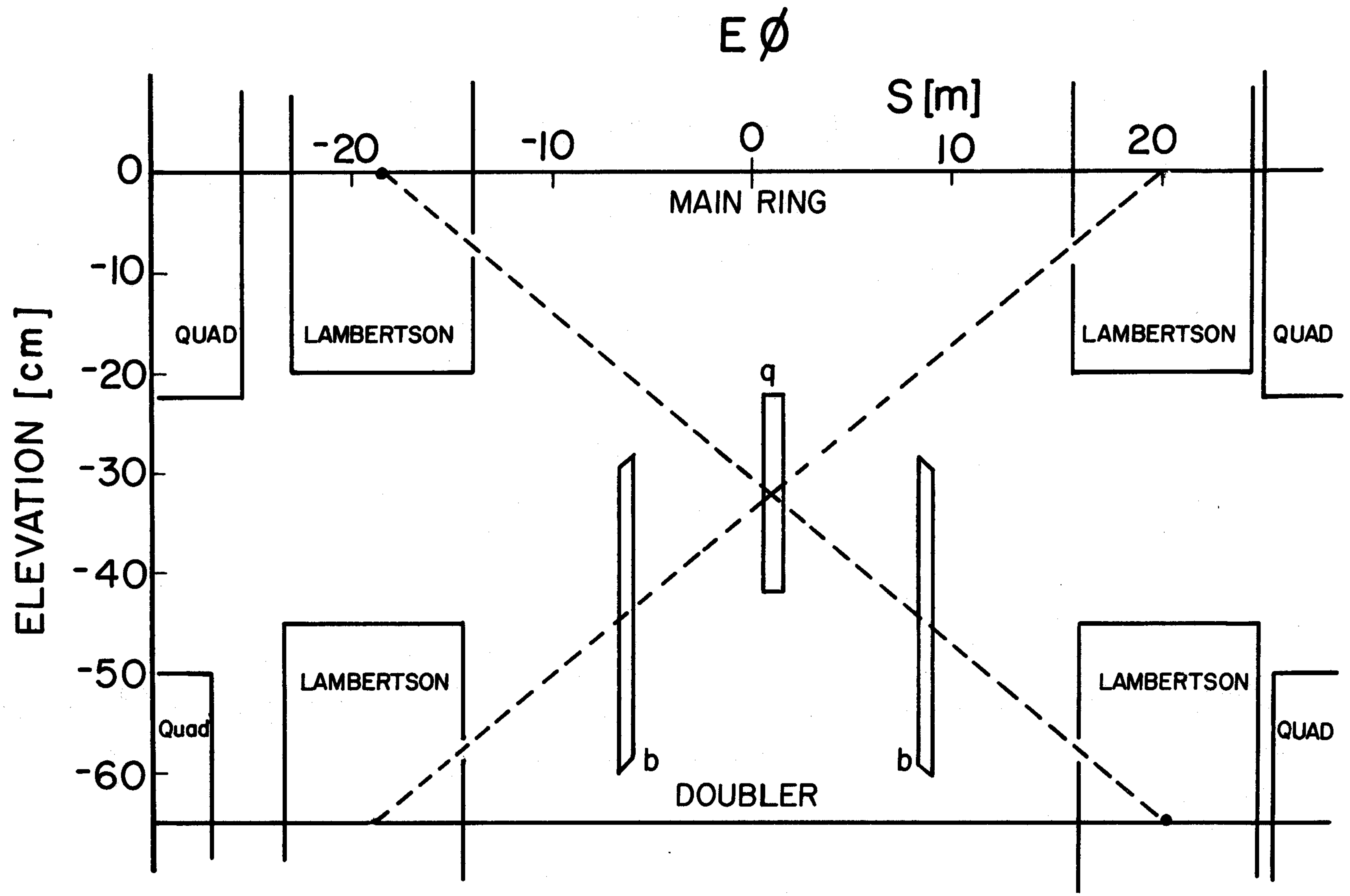

Fig. 10-3. Beam-transfer matching magnets.

Vertically, the system is two simple doglegs, each with two Lambertson magnets. In order to ease problems in the radial direction, the bend centers of those near station 49 are 7 and 8 m away from the upstream quadrupole, while the downstream ones are 5.3 and 5.0 m from the downstream quadrupole. The center-to-center distance of two magnets is approximately 39 m.

Radial positions of the beam center are shown in Fig. 10-4a for the normal-direction transfer and in Fig. 10-4b for the reverse direction. For the normal direction, the closed orbit is a combination of the natural closed orbit for $\Delta p/p = +0.25\%$ and a local bump between D46 and E17. The bump is not completely local, but the maximum perturbation outside is less than ±2 mm. In Fig. 10-4a, the beam is kicked outward by the kicker at D48 and this produces a separation of 15 mm at the septum magnet. The beam size there is ±3 mm (H) × ±4 mm (V). A three-magnet bump (D48, E11, E13) in the new ring gives a separation of 17 mm between the injected beam and the circulating beam. The kicker is at E17 and there are uncomfortable radial excursions of the beam between the Lambertson and the kicker. It may be necessary to introduce another local orbit bump (E13, E15, E17) if the excursion at 22.5 mm at E15 is too large. Steering coils in quadrupoles are strong enough to scan the entire aperture at injection.

In Fig. 10-4b, the Main-Ring kicker is at E13 and the other kicker at D48. Lambertson magnets are rotated to make small radial kicks. Specifications for the various elements are given in Table 10-I. The local closed orbit in the Main Ring between D46 and E17 is identical to the one for the normal beam transfer.

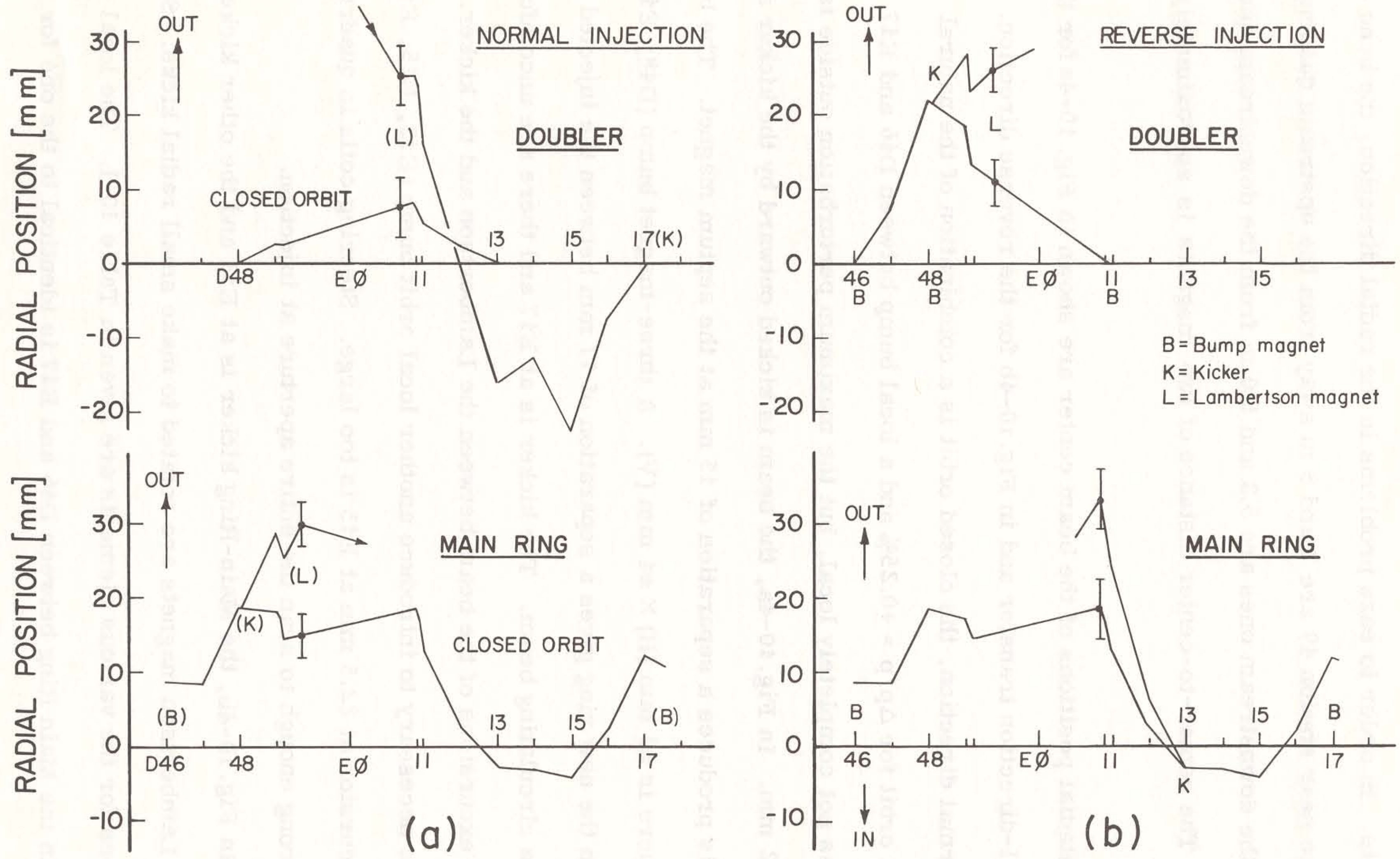

Fig. 10-4. Radial position of beam center during normal and reverse injection.

All needed spaces in the Main Ring are free of major elements. If necessary, short correction magnets can be relocated elsewhere. Since the abort system is entirely confined to long straight section C, large radial excursions of the beam exist in the superconducting ring only during slow extraction. These excursions are not excessive in E0 and there should be no problem with interference of the injection Lambertson with the extracted beam (see Fig. 8-2).

10.5 Discussion

(i) Lambertsons and fast kickers are in a way complementary. If, for example, one can use stronger Lambertsons, they can be moved towards the center (E0) to ease the requirements on kicker strength. This will have the advantage of reducing the radial beam position near the quadrupoles at both ends of the long straight section.

(ii) Steering in both radial and vertical directions must be provided. In the radial direction, local bumps in both rings can be used with a proper ratio to obtain either position-only or angle-only changes. It is easy to introduce a vertical local bump in the new ring, D47-E11-E14 for the normal transfer and D47-D49-E12 for the reverse transfer. The latter produces an almost pure position change. One probably needs vertical steering magnets between the two Lambertsons to make an orthogonal set together with these orbit bumps. One can see from the elevation view of Fig. 10-3 that there is enough space to install two steering dipoles of the vernier type 4-4-30 in addition to the matching quadrupole in the center. This dipole can produce a 0.8 mrad kick at 150 GeV/c.

(iii) Some phase-space dilution will occur during the injection process. If we require less than 25% dilution in both momentum and transverse phase space, then errors in the injection magnetic field should be less than approximately 10^{-4} and errors in position (angles) about 1 mm (10 μrad). Such position errors would be hard to obtain by dead reckoning; beam-detector readouts of the first few turns will be available for analysis and minimization of injection coherent oscillations. If the tune spread of the beam can be held to $\Delta\nu < 0.002$ by use of the chromaticity-correction sextupoles, then dampers that work over less than 50 turns can be effective.[4] The kickers alone are expected to have 2% peak-to-peak ripple over the injection time and short-duration rise-or fall-time tails and reflections of about 5% (or $2\frac{1}{4}$ mm at maximum beta positions). A damper capable of reducing these oscillations would be 3 m long, have a 6-cm gap, deflection plate voltage of ±4 kV, and a bandwidth of 5 MHz. It could produce a maximum of 1.3-μrad deflection per turn.

(iv) Since the entire injection system is confined to a relatively short distance, any perturbation in the phase advance should not affect the overall performance of the system. For example, if a low-beta insertion is introduced for colliding and if it is desirable to inject beam with the insertion on, the phase advance in a sector may change 30 degrees or more. It is easy to readjust local orbit bumps to compensate for this.

(v) The usefulness of the ring as a fixed-target accelerator will be enhanced considerably if the intensity can be increased to 10^{14}. With single-turn beam transfer, the intensity will be less than approximately

4×10^{13}. Furthermore, the beam quality certainly deteriorates as the intensity is increased in the Main Ring and this may make clean beam transfer very difficult. It would be much better if one could transfer ten turns of 1×10^{13} each; stacking in momentum space seems to be the only possibility for realizing this. Since one must avoid even a very small beam loss, it is essential that the dispersion at the kicker position (E17) be large. A high-dispersion insertion to raise η at E17 to almost 10 m has been worked out.[5] It requires different excitation of the main quadrupoles from E11 to E26. The largest change in excitations is at E11, where the amount required is $B'\ell$ = 55 kG or 19% of this focussing quad strength. This change can be excited by shunt supplies with 200-A leads. Simultaneous correction of the injected and stacked beams is another problem one must solve. Nevertheless, it seems possible to think about momentum stacking and an example was included in an earlier report.[1] For stacking, the momentum offset of the beam should be +0.05% in the Main Ring and -0.20% in the new ring. The negative offset is natural because the beam comes from inside at the kicker position, E17, as shown in Fig. 10-4.

The magnet elements needed for beam transfer are summarized in Table 10-I on the next page.

10.6 Injection Kickers and Beam Synchronization

The operation of the kickers is different for injection of p's for fixed-target physics or pp colliding beams and the injection of p's and $\overline{\text{p}}$'s for colliding beams. In the first case, 12/13 of the Main Ring will be filled with beam and transferred to the superconducting ring in a single turn. Thus

Table 10-I. Magnets and Kickers for Beam Transfer.

Beam momentum and momentum offset: 150 GeV/c, { +0.25% (Main Ring) / 0 (superconducting ring) }
Beam emittance longitudinal: 0.25 eV-s
transverse: 0.15π mm-mr

A. Elements common to both directions

1. Two bump magnets in the main ring, at D46 (1.4 m from the quadrupole) and at E17 (12 m from the quadrupole).

   $B\ell$ = ±0.84 kG-m

2. A quadrupole between two pairs of Lambertson magnets. (See Fig. 10-1)

   normal direction: horizontal focus $B'\ell$ = 18 kG
   reverse direction: vertical focus = 18 kG

B. Normal direction (see Fig. 10-3).

Main Ring

1. kicker at D48 (3 m from the quadrupole)
   $B\ell$ = 1.97 kG-m
2. Lambertson (center at 7 m from the quadrupole.)
   $B\ell$ = 9 m × 9.2 kG, rotated by 2.6°

Superconducting Ring

1. bump magnets (standard trim dipoles built in main quadrupole cryostats)
   D48: 0.44 kG-m, E11: -0.24 kG-m, E13: 0.40 kG-m
2. kicker at E17 (4 m from the quadrupole)
   $B\ell$ = 1.33 kG-m
3. Lambertson (center at 5.3 m from the quadrupole),
   $B\ell$ = 9 m × 9.2 kG, rotated by 2.2°

C. Reverse direction (see Fig. 10-4).

Main Ring

1. kicker at E13 (1.3 m from the quadrupole)
   $B\ell$ = 0.75 kG-m
2. Lambertson (center at 5 m from the quadrupole),
   $B\ell$ = 9 m × 9.2 kG, rotated by 1.3°

Superconducting Ring

1. bump magnets (standard trim dipoles built into main quadrupoles cryostats)
   D46 & E11: 1.2 kG-m, D48: -1.0 kG-m
2. kicker at D48 (4 m from the quadrupole)
   $B\ell$ = 2.13 kG-m
3. Lambertson (center at 8 m from the quadrupole).
   $B\ell$ = 9 m × 9.2 kG

there will be 19.0 μs of beam and a gap of 1.9 μs. This long gap is necessary to accommodate the rise time of the abort kicker, which is discussed in Section 11. No problem is expected in meeting or exceeding this specification for rise time of the p excitation kicker from the Main Ring or for the fall time of the p injection kicker.

For $\bar{p}p$ colliding-beam operation, individual rf buckets of p's ($\bar{p}$'s) spaced approximately 1 μs apart will be injected one at a time into the superconducting ring. By injecting single pulses, exact spacing of a specific number of rf buckets can be obtained independent of the rebunching spacing of protons in the Main Ring. For two interaction regions, a spacing of 62 buckets or 1.17 μs is required.

Once the protons are injected, individual $\bar{p}$ bunches can be injected between them. The optimal timing is for $\bar{p}$'s to pass through the injection kicker when the two nearest p bunches are equally spaced from the kicker. This equalizes kicker rise- and fall-time requirements. Once all bunches have been injected (usually twelve of each), the azimuthal position of the crossing can be adjusted to coincide with the center of the interaction region. The two orthogonal rf systems discussed in Section 9.2 will be run at slightly different frequencies until the proper azimuthal relationship of p's and $\bar{p}$'s has been obtained.

There are a total of four magnet systems. The kicker specifications are given in Table 10-II. The p extraction kickers and injection kickers are to be used in both fixed-target and $\bar{p}$ colliding-beam operation. Three of the systems will require matched lumped-element transmission-line

Table 10-II. Kicker Specifications.

	p Extraction fixed target	p Extraction $\bar{p}p$ mode	p Injection fixed target	p Injection $\bar{p}p$ mode	$\bar{p}$ Extraction	$\bar{p}$ Injection
$B \times \ell$	1.97	1.97	1.33	1.33	0.75	2.13 kG-m
Pulse Length	20.0	0.01	20.	0.01	40	0.01 μs
Rise Time 0-100%	0.4 n	0.4	-	0.4	20	0.5 μs
Fall Time 100-0%	-	0.4	0.4	0.4	20	0.5 μs
Magnet Impedance	25 Ω	25 Ω	12.5 Ω	12.5 Ω	5.625 μH	12.5 Ω
# Modules	5	5	1	1	1	1
PFN Impedance	8.3 Ω & 12.5 Ω	8.3 Ω & 12.5 Ω	12.5 Ω	12.5 Ω	45 μf	12.5 Ω
Magnet Module Length	1.0	1.0	2	2	1.5	3.5 m
Field	400	400	670	670	500	600 G
Gap (V × H)	2 × 6	2 × 6	2 × 2	2 × 2	2 × 6	2 × 2 in.^{2}
Charging Voltage	80	80	67	67	1.5	60 kV

magnets, because beam will circulate through their aperture after the kicker is fired. The rise and fall time of 0.5 μs should be more than adequate for any colliding-beam operation. The only system exempt from these requirements is the $\bar{p}$ extraction kicker. It can be a simple 40 μs half-sine-wave device because we plan to have only one $\bar{p}$ bucket at a time in the Main Ring.

Electronic schematics for the four kickers are given in Figs. 10-5 to 10-8. The p extraction kicker is composed of two parallel sections and can produce either short or long pulses. In the case of the long pulse both the cable and the lumped delay lines are charged, and both the main and long-pulse thyratrons fired. For the short pulse, only the front-end PFN's need be charged and only the main thyratrons need be fired.

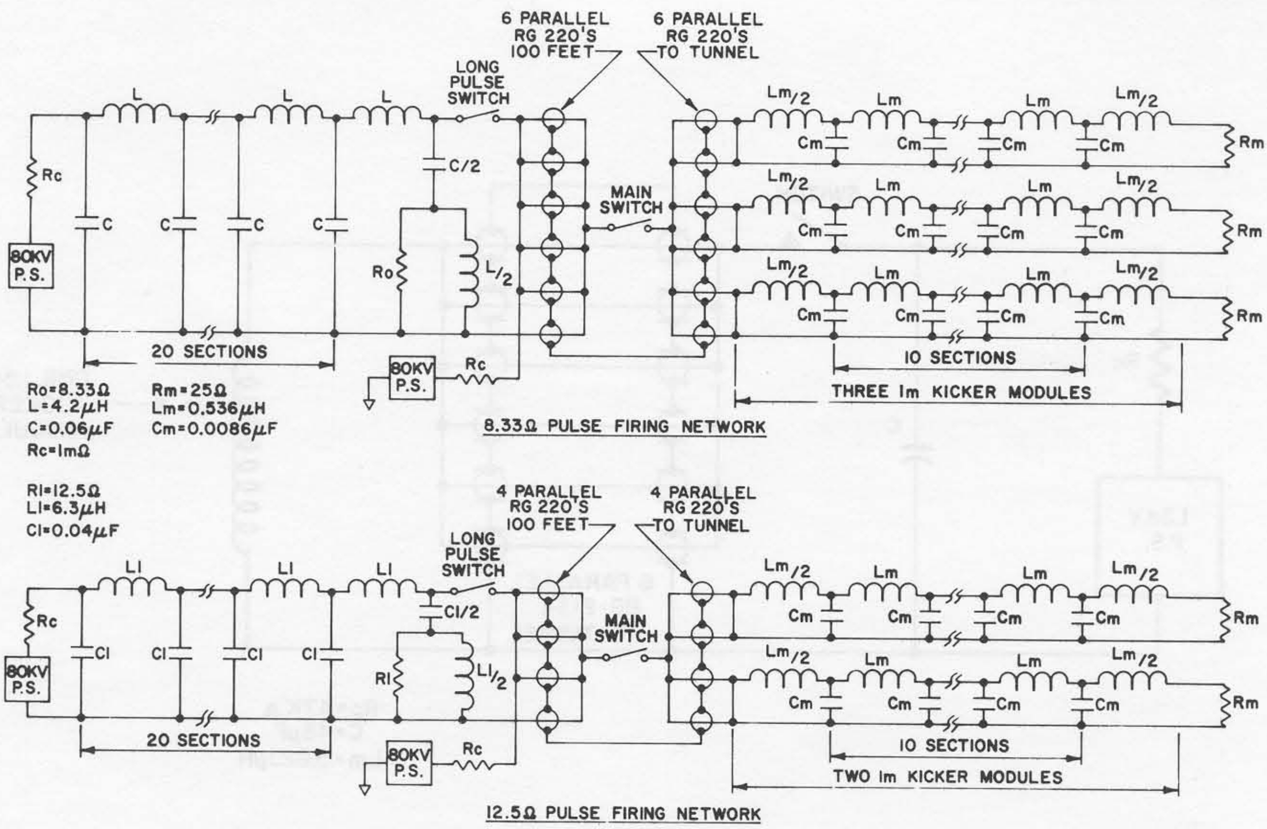

Fig. 10-5. Proton extraction kicker.

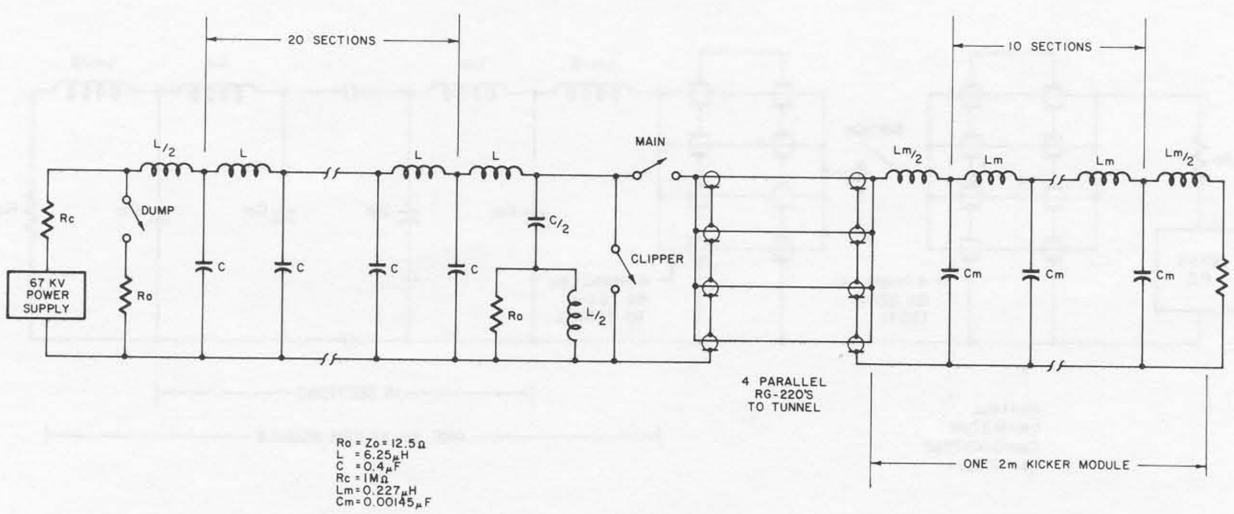

Fig. 10-6. Proton injection kicker.

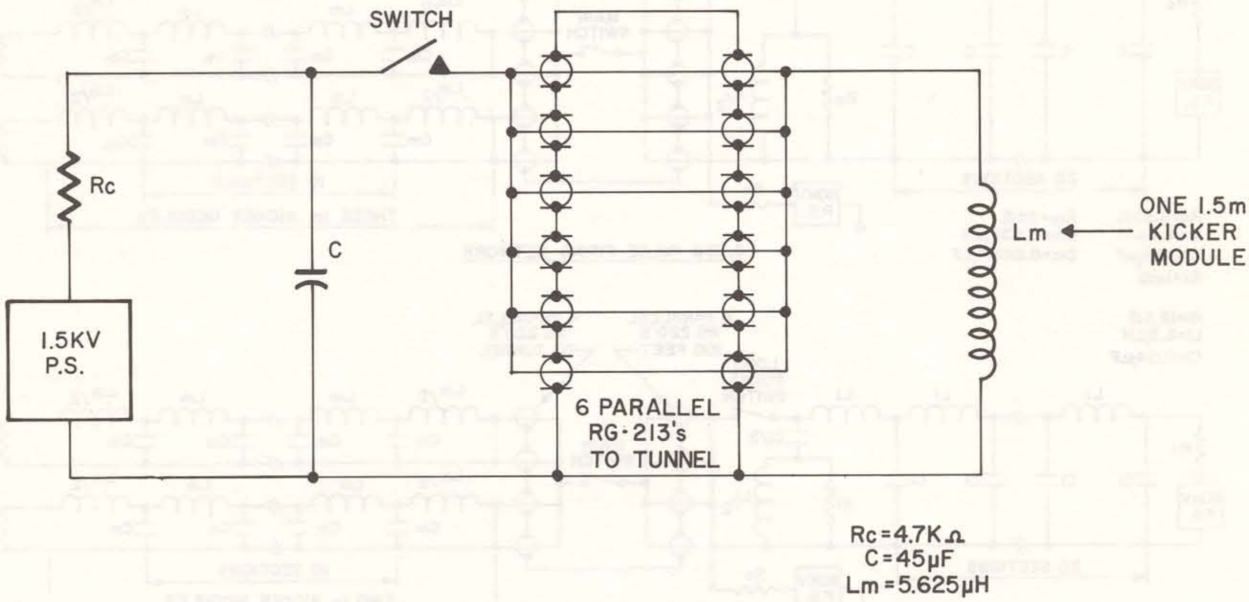

Fig. 10-7. Antiproton extraction kicker.

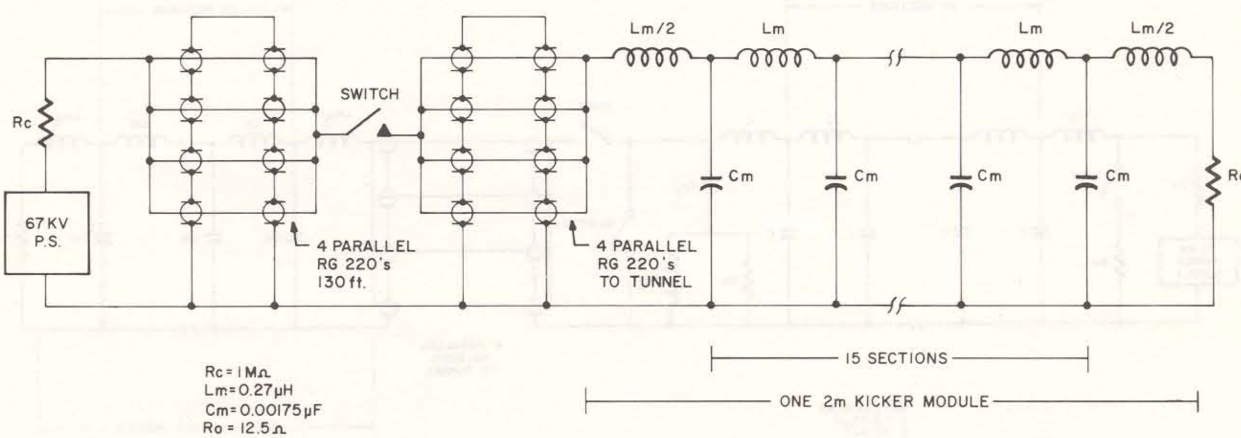

Fig. 10-8. Antiproton injection kicker.

In order to produce the fast fall time for the p injection kicker, two additional thyratrons are needed, one to act as a clipper to generate the fast fall time and one as a dump to terminate reflections from the clipper. These are shown in Fig. 10-6. This system can be used also to produce the short pulse for p injection for colliding beams by appropriately timing the clipper and dump switches relative to the main switch.

The $\overline{p}$ extraction kicker is a simple SCR device similar to the Main-Ring pingers.

Figure 10-8 shows the proposed $\overline{p}$ injection kicker. A lumped delay line is not necessary because of the short pulse length.

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