8. EXTRACTION SYSTEM

8.1 Orbit Design

The basic design goals of the extraction system are (i) provision of slow resonant extracted beam with uniform spill over times of 1 to 10 s; (ii) provision of fast resonant extracted beam in the range of 1.0 to 3.0 ms (multipulsed fast extraction is also desirable but presents intrinsic problems in maintaining good extraction efficiencies; the designed extraction system should not be incompatible with this goal); and (iii) the extraction efficiency should be high (losses < 2%) to minimize beam-loss effects on the superconducting magnets.

An accurate estimate of the available effective magnet aperture is essential when considering the extraction process in detail, because extraction will explore fully and be limited by magnet aperture. During the extraction cycle, the maximum-amplitude orbit excursions increase monotonically from turn to turn and each particle will therefore achieve its maximum amplitude on the final turn before being extracted. In order to calculate the effective aperture of a perfectly aligned accelerator with perfect design fields, we must consider a slightly off-momentum orbit, on which the higher-order odd harmonics do not cancel. A momentum offset of 0.05% will give an average orbit offset of approximately 1.5 mm, representative of the operational tolerances that can reasonably be expected. Figure 8-1 shows data resulting from an analysis of this kind. We have plotted the phase-space trajectory for a half-integer extraction separatrix at the upstream ends of the long straight sections sequentially around the ring, starting at B0.

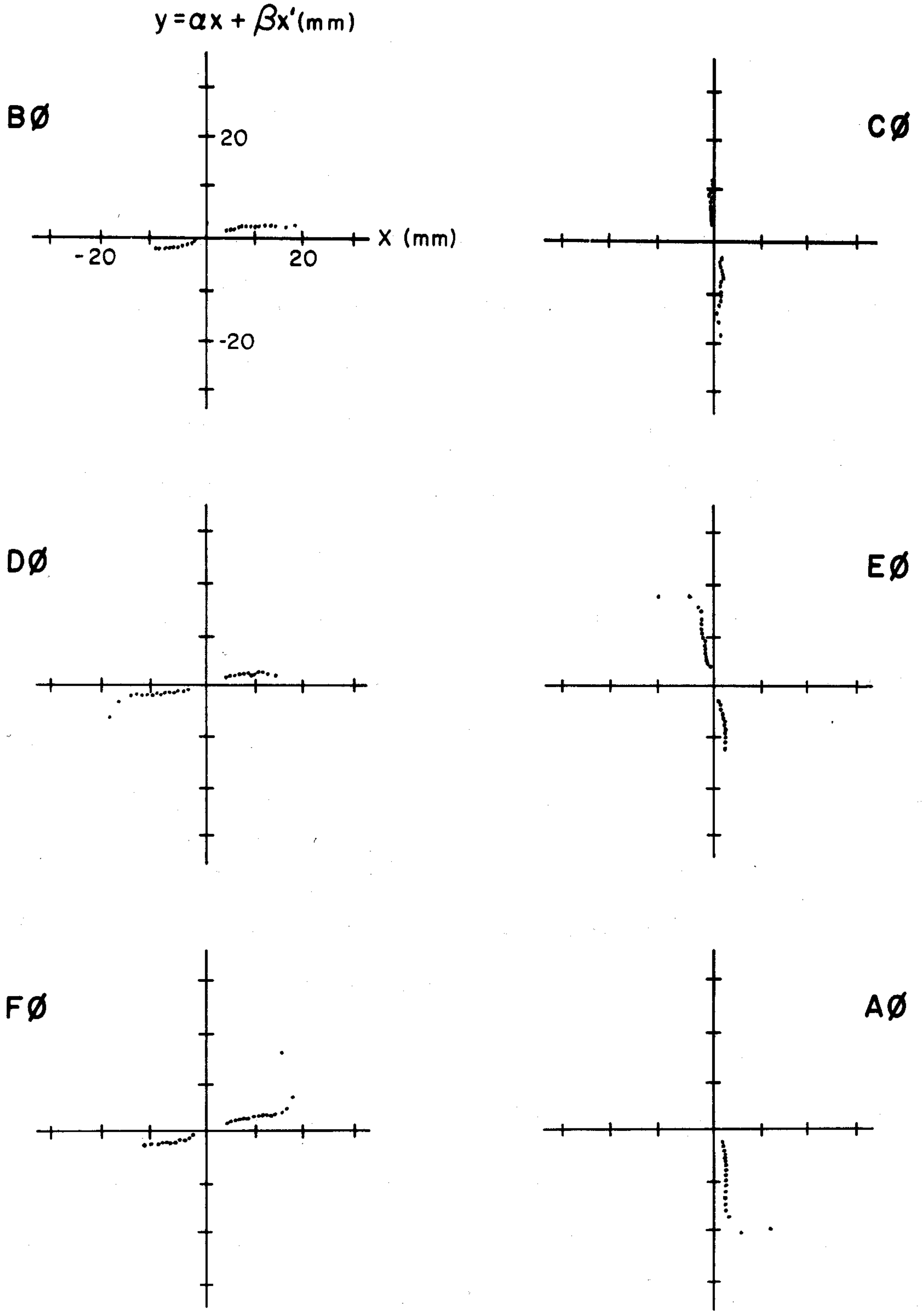

Fig. 8-1. Half-integer slow-extraction separatrix around the ring without high beta.

The growth of the radius vector around the cycle is evident and, starting with the D0 long straight section, we can see the effect of the higher-order terms in the dipole-field harmonics starting to manifest themselves as rotations in the phase-space trajectory; these rotations get progressively larger during the cycle. From a more complete analysis[1,2] we conclude that the horizontal aperture is slightly larger than the vertical aperture and henceforth we shall only consider horizontal extraction. We also find that we need to control the vertical closed orbit to within ±3 mm of the dipole center. With this limitation, the maximum-amplitude orbit oscillations must be within ±2 cm, with the exception of the final few oscillations in the ring, which can grow to approximately ±2.5 cm without any major phase-space distortions. The effect of this 2-cm aperture limitation on the extraction system was too severe and would result in unacceptably high extraction losses if the lattice were the same as that of the Main Ring.

The solution of these problems[3] is to redesign the long straight sections containing the magnetic and electrostatic septa to provide a five-fold increase of the amplitude-function β of the lattice at the upstream end of the long straight sections. The layout of a high-β long straight section is shown in Fig. 2-3. Three different-length quadrupoles are introduced in the 48, 49, 11, and 12 locations, with the polarity of the quadrupole doublets at 49 and 11 reversed from the normal long straight section. The lattice parameters across the high-β

sections are matched to those of the normal lattice. The effect of this lattice modification on resonant extraction has been studied in detail.[1,4] It increases the effective aperture available to the extraction system by a factor of 1.8, which permits a greater extraction efficiency with a more stable extracted beam. The effective strength of the electrostatic septum is increased by a factor of 4.5, which allows the use of a shorter septum than previously and, possibly more important from an operational point of view, allows the extraction septa to be located at the upstream end of the long straight section, permitting the maximum amount of shielding of the downstream superconducting magnets from the primary and secondary products of the extraction losses. The lattice with two high-β long straight sections is discussed in detail in Section 2.

Resonant extraction could be accomplished in either third-integer or half-integer modes. Implementation of both forms is not practical at the outset and consequently a choice between them must be made. A detailed comparison between the relative merits has been done.[5] Slow extraction efficiencies are almost identical for the two cases. Slow spill of the entire beam is easier in the half-integer system. The requirements of fast resonant extraction overwhelmingly indicate a preference for half integer and we have therefore chosen half-integer resonant extraction as the operational system.

8.2 Slow Extraction

We can now begin to formulate the layout of the individual elements and their operational characteristics. The choice of long straight-section A is dictated by the extraction channel to the existing external experimental areas. The magnetic septa (Lambertson magnets) will be located at the upstream end. The presence of the Main-Ring rf cavities at F0 does not leave room for the electrostatic septum and as a result, it will be located at the upstream end of long straight-section D. The appropriate harmonics for the quadrupoles (39th) and the octopoles (39th and/or 0th) needed for slow extraction will be provided by the correction-coil package (discussed in Section 7), which will also allow control over the relative phase of the 39th harmonic. In order to inhibit the growth of the oscillation amplitude between the electrostatic and magnetic septa on the final half turn for the extracted beam, only the correction coils in sectors A, B, C, and F will be used in the extraction system. An analysis of 1/3-integer extraction[4] shows that for fixed phase-space trajectory and available aperture, the optimum extraction efficiency is achieved when the electrostatic-septum offset and the step size across the septum are equal. This sort of criterion can be used to calculate the relative strengths of quadrupole and octopole needed for extraction. Figure 8-2 demonstrates the behavior of the slow-extraction separatrix around the ring, incorporating all of the factors discussed above. The effect of the high-β sections at A0 and D0 is apparent in increasing the beam amplitude at these points. The septum offset at D0 is 12 mm; the step size is adjusted to be 12 mm. This represents the limiting case of the magnet aperture; the average orbit amplitude over the last half turn is approximately 25 mm. The

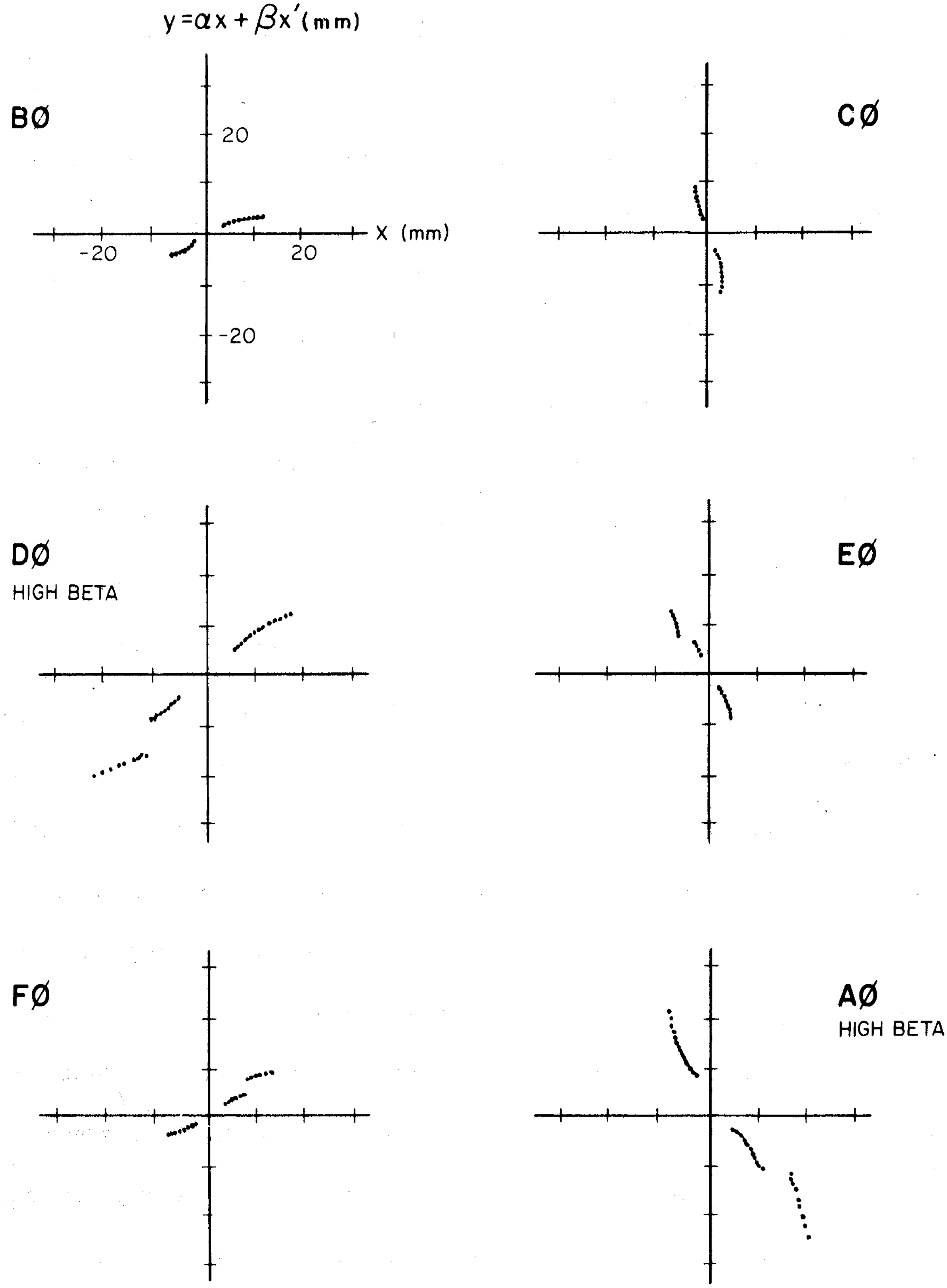

Fig. 8-2. Half-integer slow-extraction separatrix around the ring with high beta.

integrated field strength of the quadrupoles and octopoles in this case is 255 kG-in. and 412 kG-in. respectively at 1 in. The extraction losses of a system with these operational parameters are approximately 1.5%, for a 3-mil effective septum thickness.

8.3 Fast Resonant Extraction

Fast resonant extraction is accomplished by using the slow-extraction elements to bring the beam close to resonance and then firing a series of fast-pulsed quadrupoles to drive the beam into resonance. The strength of the pulsed quadrupoles is determined by the requirements on spill duration. We have studied[6] a fast-extraction system that satisfies the design criteria. The active elements consist of four pulsed quadrupoles located in the warm 48 lattice positions in sectors A, C, D, and F. Work is currently in progress on a Monte Carlo simulation of this fast-extraction system. Figure 8-3 on the next page shows a sample phase-space output at the magnetic septum. The initial results indicate that the required maximum field strength necessary for each element is approximately 25 kG-in. at 1 in. for a 3-ms half-sine-wave pulse. A list of the active extraction elements with their typical operational parameters is given in Table 8-I on the next page.

8.4 Straight-Section Layout

A detailed layout of the D0 long straight section from C49 to D11 is shown in Fig. 8-4 on page 145. The superconducting magnets downstream of D11 are shielded from the extraction losses by a vertical dogleg produced by the bending magnets B1, B2, and B3 and an aperture-limiting scraper downstream of the electrostatic septum. The amplitude of the vertical dogleg is approximately 6 cm. Detailed results of a Monte Carlo study of the loss

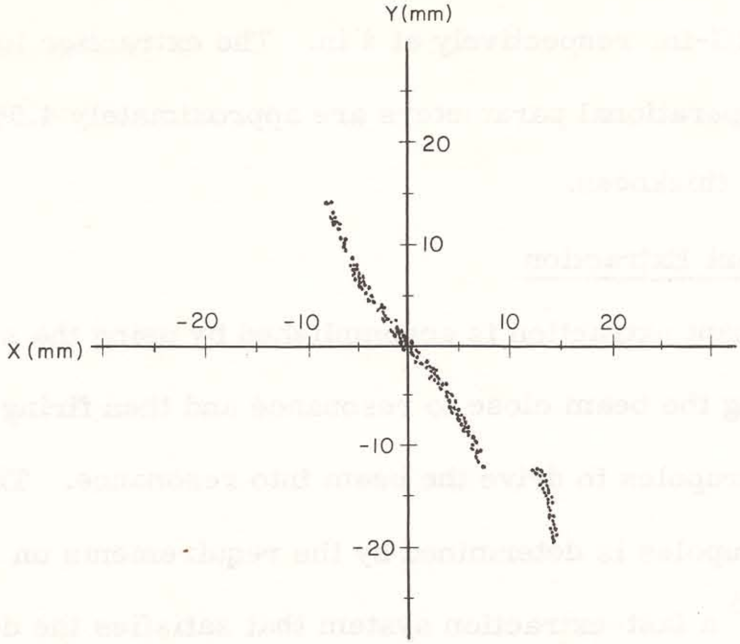

Fig. 8-3. Separatrix for half-integer fast resonant extraction.

Table 8-I. Extraction Elements.

Element	Position	Parameters
Electrostatic Septum	Upstream D0 long straight section	length 6 m gap 16 mm voltage 75 kV
Magnetic Septum	Upstream A0 long straight section	length 95.5 ft field 12 kG
Slow extraction	Correction coils A, B, C, F (28,42) sectors (stations)	255 kG - in. total quadrupole at 1 in.
Slow extraction	Correction coils A, B, C, F (28,42) sectors (stations)	412 kG - in. total octopole at 1 in.
Fast extraction Quads	A48, C48, D48 F48 mini-straight	25 kG - in. at 1 in. (max) per element for 3.0 ms half sine wave pulse

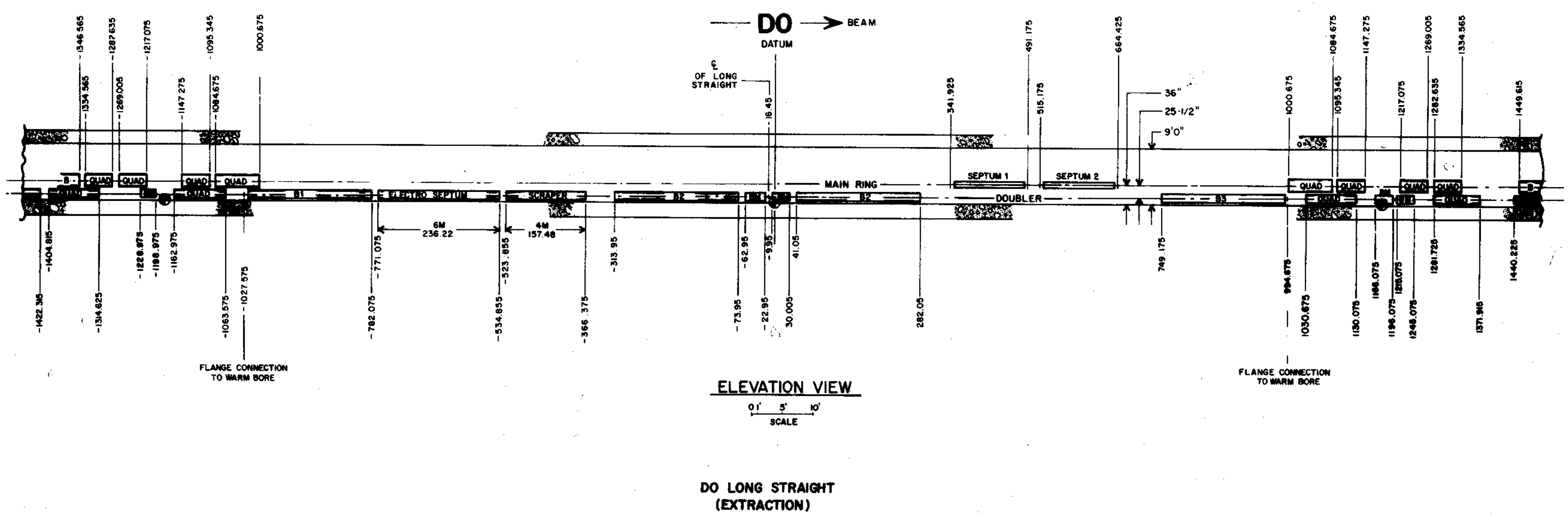

Fig. 8-4. Layout of D0 long straight section.

distributions associated with this design are presented in Section 13 of this report. Local orbit control is provided by the conventional bump magnets located as shown, together with one in the C48 mini-straight section. With this system of bump magnets, we have a maximum spatial offset at the septum of 7 mm and an angular range of 150 μrad.

8.5 Extraction Channel

One of our basic design goals with the extraction channel has been to produce a layout that maintains compatibility with the continued use of the Main-Ring extraction facility. The design we are presenting here fulfills this criterion. The layout of the A0 long straight section is shown in Fig. 8-5. The initial beam separation is accomplished by 5 Lambertson magnets, each 220 in. in length with a 12.5-kG field at 1 TeV, producing a total vertical bend of 10.48 mrad, which results in a vertical displacement of 6.005 in. from the circulating beam at the downstream end of the magnets. The extracted beam is then deflected both horizontally and vertically by a series of three standard superconducting dipoles powered in series with the superconducting ring magnets. This string of magnets, rotated by 19.05° from the horizontal, produces a 23.019-mrad radially outward bend and a downward deflection of 7.948 mrad. A horizontal trim magnet 40 ft further downstream is then used to adjust the beam trajectory to produce a simultaneous horizontal and vertical intercept of the beam with the existing extraction channel upstream of Switchyard Enclosure B. At this point, the beam is deflected into the current extraction channel by a Main-Ring dipole, rotated by 32.06° from the vertical position, on a trajectory similar to the Main-

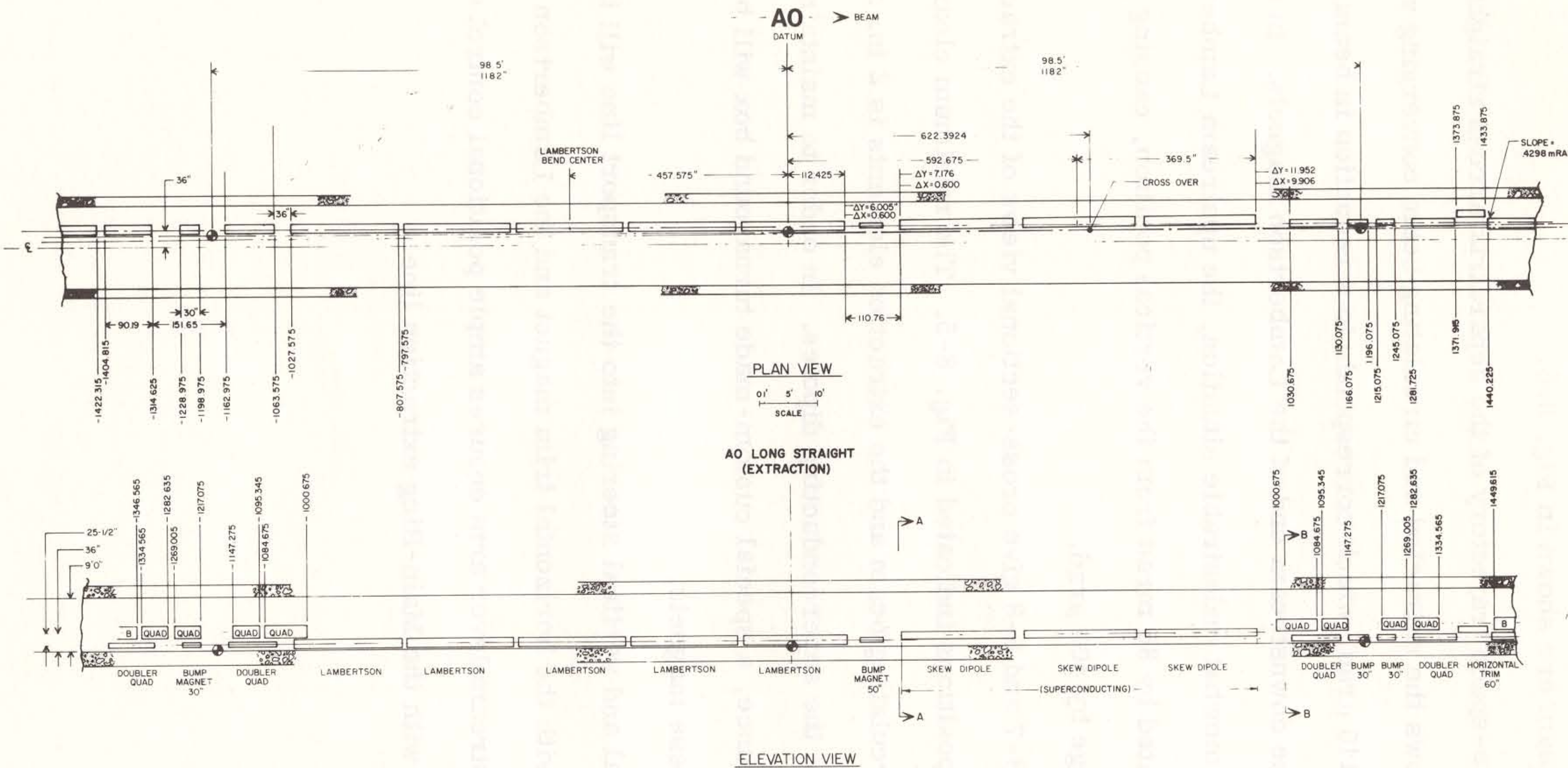

Fig. 8-5. Layout of A0 long straight section.

Ring extracted beam. The detailed horizontal and vertical geometries of the extracted beam are shown in Fig. 8-6.

The phase-space trajectory of the separatrix across straight-section A in Fig. 8-2 shows the extracted and circulating beam converging with a maximum angle of 110 μrad, which corresponds to a reduction in beam separation of 1.2 mm at the downstream end of the Lambertson magnets. In order to correct this somewhat undesirable situation, the upstream Lambertson magnet will be rotated by 85 mrad from the vertical position, causing the two beams to diverge by 100 μrad.

Figures 8-7 and 8-8 give cross-sectional views of the extraction channel at the positions indicated in Fig. 8-5. The minimum clearance between the circulating beam and the extraction elements is 2 in. at the upstream end of the superconducting dipoles. In order to maintain this minimum clearance, a special custom-made turnaround box will be required for these magnets.

Horizontal and vertical steering into the transport line will be accomplished with the horizontal trim magnet and the Lambertson string. The long downstream lever arm ensures ample positional control at the intercept point with the Main-Ring extraction line.

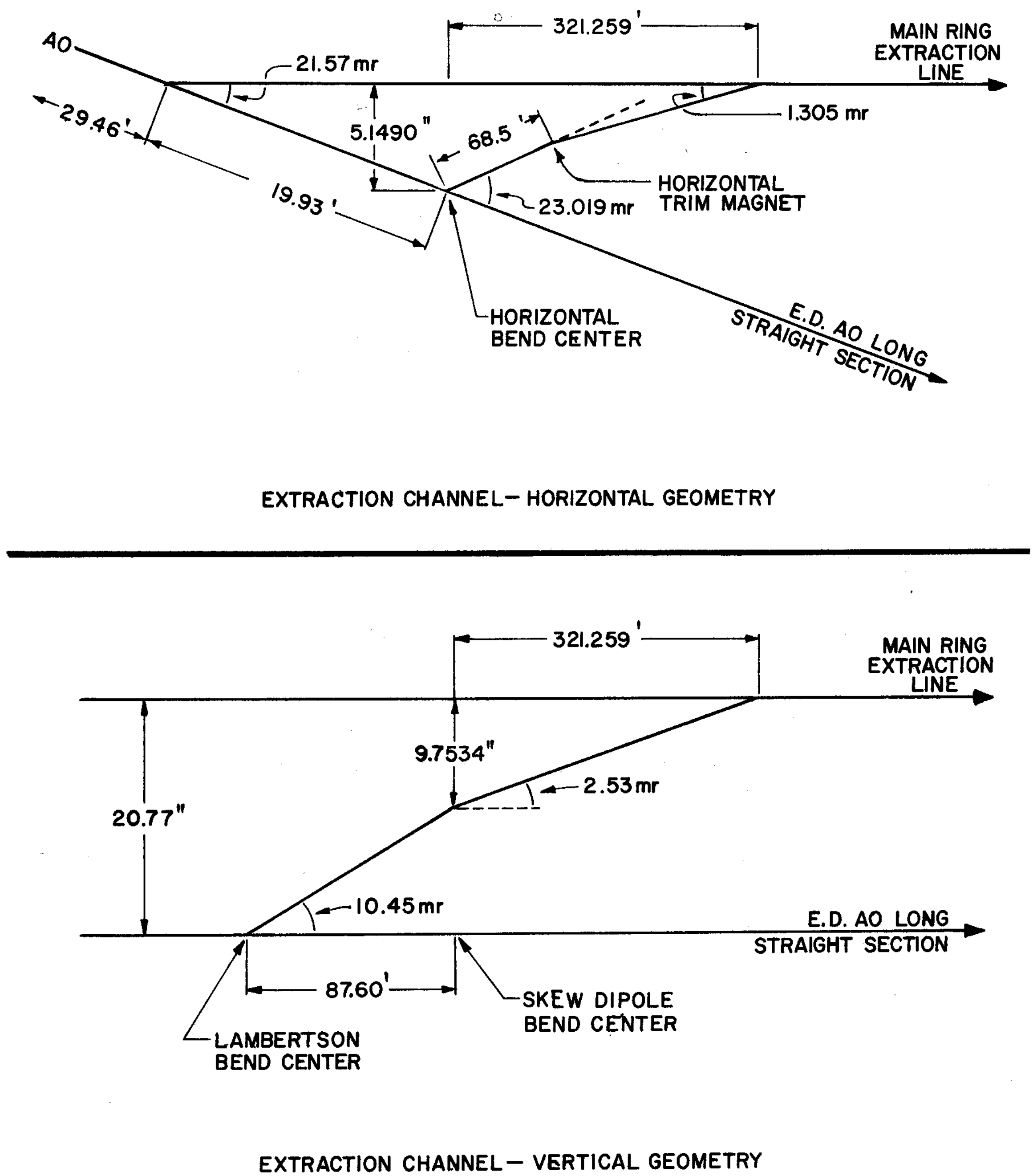

Fig. 8-6. Horizontal and vertical geometry of the A0 extraction channel.

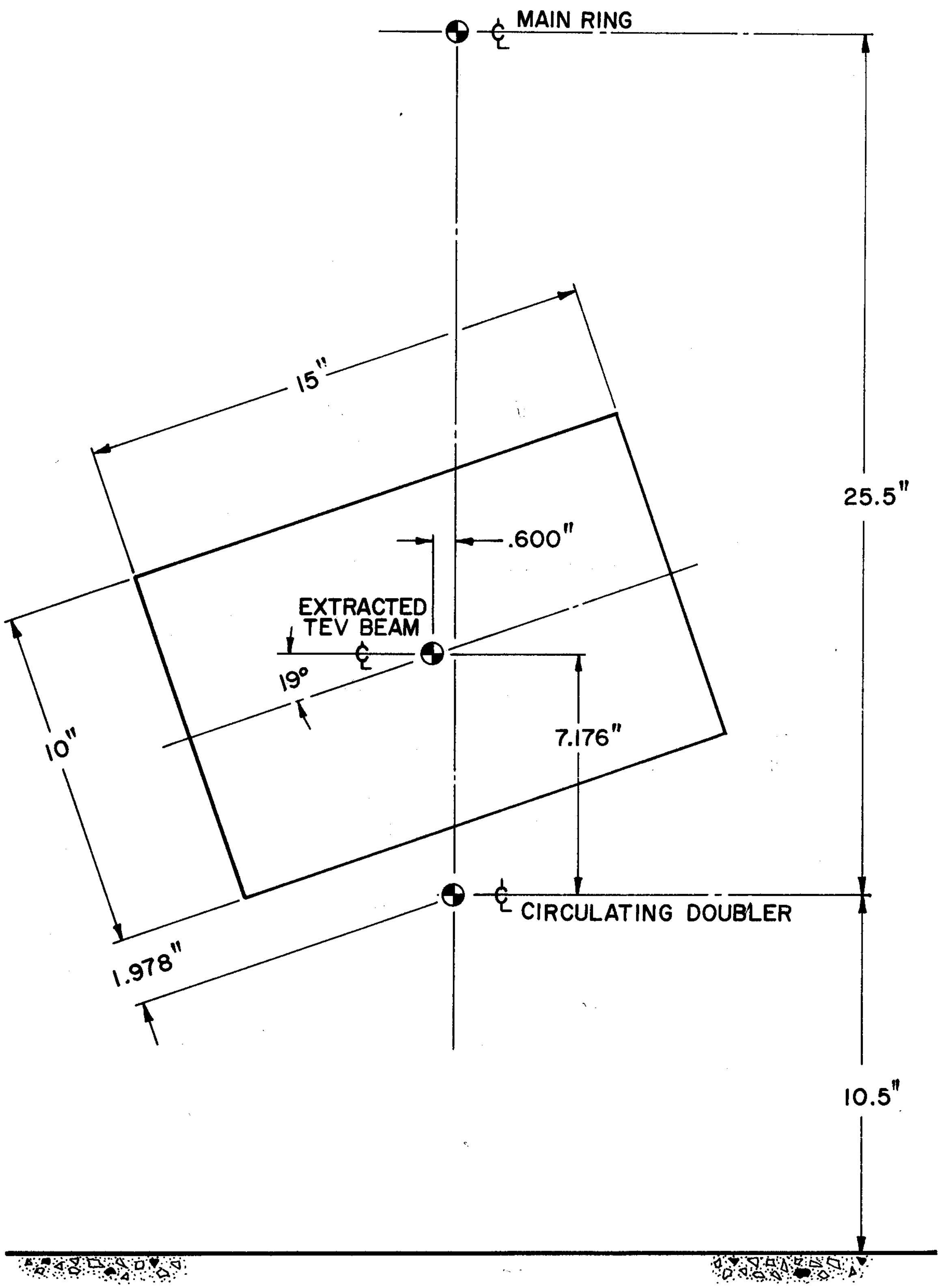

Fig. 8-7. Cross section AA of the extraction channel.

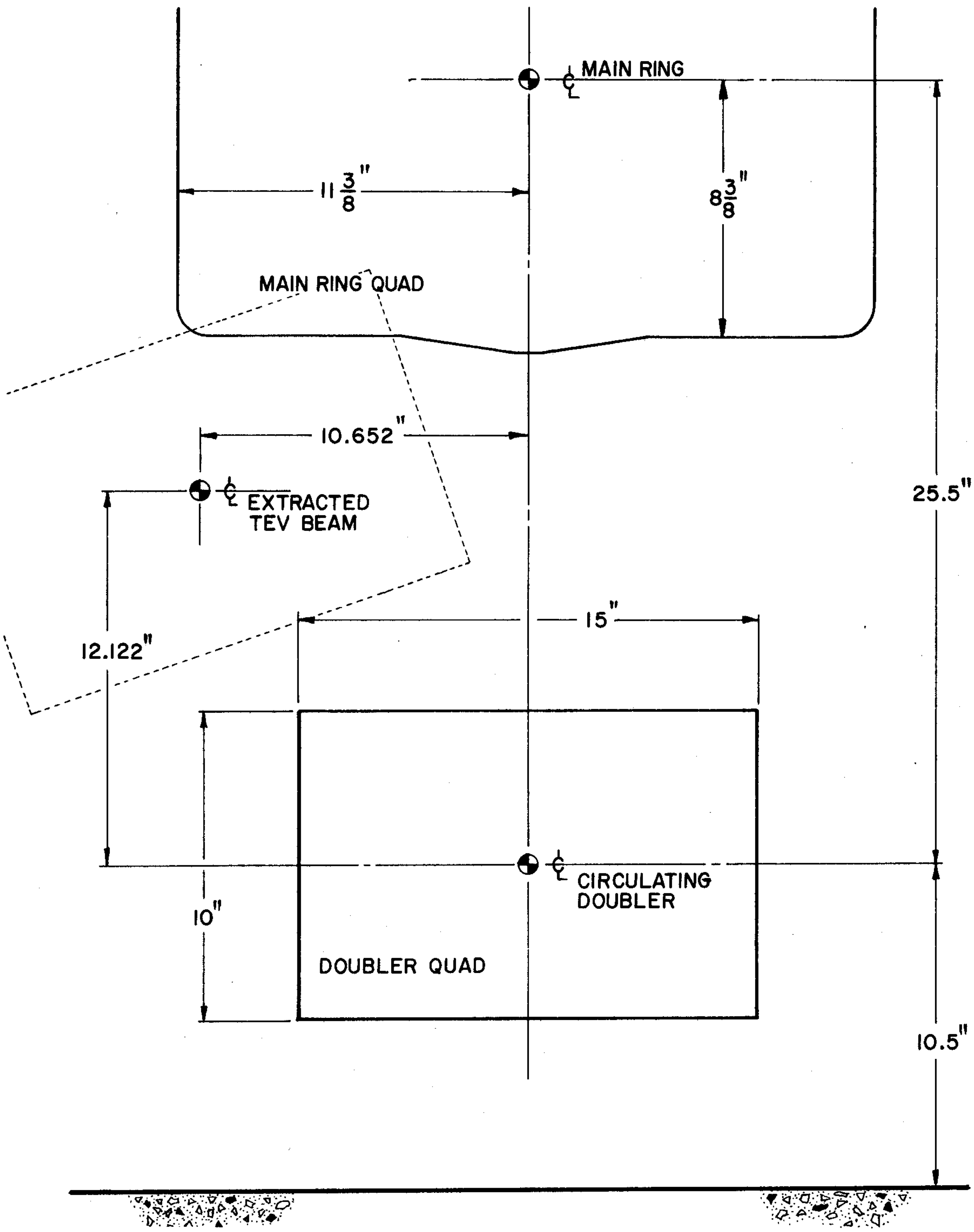

Fig. 8-8. Cross section BB of the extraction channel.

References

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[5] D. A. Edwards, Comparison of Half Integer and Third Integer Extraction for the Energy Doubler: 1. Basic Processes, Fermi National Accelerator Laboratory UPC No. 34, December 1978.

[6] M. Harrison, Extraction III - Fast Resonant Extraction, Fermi National Accelerator Laboratory UPC No. 87, February 27, 1979.