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HIGH ENERGY PHYSICS
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Abstract

A fast beam extraction system is designed for the KEK 12 GeV Proton Synchrotron. The extraction is performed by the multi-turn beam shaving method in which hyper thin electrostatic septum inflectors are used as shaving elements. The beam loss and the emittance of the extracted beam are analyzed numerically as a function of thickness of the electrostatic septum wires. Specifications of the extraction elements, electrostatic septa, fast and slow bumps, and septum magnets, are given for the configuration of the designed system.

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* On leave of absence from Fermi National Accelerator Laboratory

§1. Introduction

Proton beams accelerated in the KEK 12 GeV PS are delivered to two halls for high energy physics experiments. (Figs.1 and 2) A 1 meter hydrogen bubble chamber is housed in the hall A-102 and operated for fast spill beams extracted at the long straight section II-2F of the main ring. In the hall A-100, electronic counter experiments are performed utilizing slow spill beams extracted at III-2F.

Usually a fast spill beam is obtained by use of fast kicker magnets. A very high extraction efficiency, reaching almost 100%, can be achieved by making the rise and fall time of the kicker magnets faster than circulating beam bunch separation. The intensity of the extracted beam is determined by the number of bunches extracted. This method, however, has the disadvantage in that it cannot be applicable to debunched beams.

On the other hand, recent developments of high voltage electrostatic deflectors have made it possible to shave out an accelerated beam continuously over several turns in the PS. The loss of beam hitting the septum is kept within a tolerable amount by use of a very thin septum plane, wires or foils. Advantages of this scheme are that, (1) the extraction can be made for debunched beams and operated simultaneously with slow extraction process, and (2) smaller horizontal emittance of extracted beam than that of the internal beam is expected by shaving the beam out horizontally. These features cope with the requirements of the bubble chamber group for slow spill beams to the bubble chamber experiments, and leave a possibility of building a new electronic counter experiment hall along the beam line from the straight section II-2F.

When this method is applied to the KEK PS, the extraction process proceeds as follows. Before starting the extraction, the circulating beam, bunched or debunched, is pushed onto the electrostatic septum deflectors (II-1F) by means of two pairs of slow bump magnets (I-7F, II-3F and I-7D, II-3D). The extraction is initiated by pulsing a pair of fast bump magnets (I-7F and II-5D), which produce a local orbit shift at the electrostatic septum. A fraction of particles displaced across the first electrostatic septum is deflected into thin septum magnets (II-1F and II-1D), and fully extracted through three ejector magnets in II-2F. By increasing the field of the fast bump magnets, the beam is extracted over several turns in the ring.

In the followings, we present orbit calculations, and configurations and specifications of each element of the system. The beam loss and the emittance of the extracted beam are also analyzed numerically as a function of the thickness of the electrostatic septum wires.

§2. Electrostatic Septa

The lattice structure of KEK provides two long straight sections for fast extraction of the 12 GeV proton beam. The straight sections are formed by the removal of bending magnets following focusing quadrupole in the regular unit cell, and are separated by a defocusing quadrupole and bending magnet. This separation results in a betatron phase difference of approximately π/2 radians. The straight sections are 5.46 meters in length, but the first 0.8 meters are utilized for beam monitoring equipment and a steering magnet leaving 4.66 meters of usable space.

The first straight section, II-1F-LS, will be used to produce the initial beam split, and the second, II-2F-LS, will contain the main bending elements in the extraction system.

The amount of bend required in the initial straight section to provide a 15 mm split in the second straight section is determined both by the septum thickness and the beam emittance. The first extraction magnet located at the upstream end of the second straight section has the septum coil of 15 mm thick. Figure 3 shows a standard ellipse at 0.8 meters into either straight section. The emittance was assumed to be 16.6 (π)mm·mr. The line AB indicates the position of the septum plane at the upstream end of the first straight section. The particles to the right of the line AB in the first straight section will have rotated so as to be contained in the area below the curve drawn from C to D by the beginning of the second straight section. Thus, the initial split must produce enough bend to displace point D by 15 mm in addition to the distance from point D to the outside of the ellipse, or a total displacement of approximately 44 mm at the beginning of the second straight section.

The initial intent in the design of the system was to use electrostatic septa to produce the initial beam split. This type of septum can be made very thin (0.05 mm) and is thus ideal for a shaving extraction. The field strength presently obtainable with electrostatic septa is about 60 kv/cm. A field of 60 kv/cm will result in a bend of 0.47 mr/m for

12 GeV protons. This bend strength is quite weak and thus the electrostatic septa alone cannot produce the required displacement. In order to minimize losses and still produce the necessary displacement, a combination of electrostatic septa and thin magnetic septa is used.

Figure 4 shows an outline of II-1F long straight section and II-1D-short straight section. The electrostatic septa have a 15 mm gap and a field strength of 60 kv/cm. With 3 meters of electrostatic septum, the final separation for parallel particles is 2.53 mm, however, as a result of the large angular divergence of the beam, the first magnetic septum must be 1 mm thick or less. In order to produce the required 15 mm split in II-2F-LS, this thin septum must have a bend strength of 1.5 kG-m.

Since this septum is just before a defocusing quadrupole, and β_V is large, the current required would be in excess of 5000 amperes. Thus, another similar septum must be placed after the defocusing quadrupole (II-1D), and then the current requirements on both can be reduced.

The field strength of the first septum magnet is 700 gauss and it is 1.11 meters in length. This results in a beam separation of 4.65 mm at the entrance of the second magnetic septum. The second septum magnet is .8 meters in length and has a field strength of 1400 gauss. Thus, the second septum can be two turns and powered in series with the first. For 50 mm high septa a current of 2785 amps is required.

A minimum thickness electrostatic septum has a wire size of 0.05 mm and a wire spacing of 1.25 mm. For a particle to pass into the field region of such a septum (or out of it) without interacting with a wire, it must have an angle in excess of θ relative to the septum, where

$$\theta = \text{arc sin } (0.05/1.25) = 40 \text{ mr.}$$

Figure 5 is a section of Fig.3 with line AB as the verticle axis, line FG as the horizontal axis, and normalized so that point E is the origin. If the upstream end of the electrostatic septa were placed at the position of point E, and the septa were aligned along the angle of E, then this graph represents the positions and angles of the beam relative to the electrostatic septa.

From Fig.5 it can be seen that no particles have angles large enough to pass through the septum without interacting with the wires. Since the wires are small on the scale of Fig.5, the thickness of the wires does not determine how many particles will interact with the wires, but rather the distribution of the scattering angles.

In Fig.5, all the particles bounded by IJ, the emittance ellipse of the beam and the vertical axis will interact with an infinitely long electrostatic septum. The curve IJ was determined by assuming that the beam was bend away from the septum by $\frac{1}{2}\phi_{ES}$ on either side of the septum, where ϕ_{ES} is the bend/meter (mr/m) of the E.S. septum. Actually, the particles are bend away from the septum by ϕ_{ES} inside the field region and are unaffected outside of the field. In order to approximate the foregoing, the septum must be segmented and placed along the line formed by a bend of $\frac{1}{2}\phi_{ES}$. It can be shown that the maximum initial displacement from the septum X_{MAX}, for interaction with the wires, is

$$X_{MAX} = \phi_I^2/2\phi_{ES} \quad \text{(mm)} ,$$

where ϕ_I is an initial angle (mr) toward the septum. All the particles located along the lines K-L and K'-L' will interact with the septum at one meter, and thus, all particles contained in the areas Q and Q' will interact with the first meter of septum. Likewise, MN, M'N', R and R', and OP, O'P', S and S' represent the same functions for the second and third meter, respectively.

A computer program was used in order to determine the effect of the Coulomb scattering of the wires of the electrostatic septa, and finally, the predicted efficiency of the system. The calculation was based on an emittance of 16.6 (π) mm•mr.

The septa were divided into 1 cm sections. Any particle incident on a 1 cm section of wires received an angle

$$\phi_{scatt} = 2.24 \sqrt{D\cos(P)}{}^{*}R ,$$

where D is the diameter of the wire (mm), R is a gaussian distributed random number with standard deviation equal to 1, and P is a normalized position of the particle. This position is normalized to the wires with the center of the wire equal to 0 and the edges of the wire equal to $\pm\pi/2$. This number assumes that the wires are tungsten and the wire spacing is 1.25 mm. The angle of the particles inside the field region of the septa were increased by 4.7 microradians from each section. After traversing the septa, the particles were checked for collisions with the 1 mm septum at the end of the electrostatic septum in the first long straight section and the 15 mm septum in the following long straight section. The extracted particles were also checked in the extraction straight section for excessive displacement, which is due to large angle scattering. Excessive displacement was defined in the program as a displacement in excess of 74 mm at .8 meters into the II-2F-LS (the entrance of the first extractor magnet). The unextracted particles were transformed through the machine matrix and the effect of slightly mismatched fast bumps was taken into account. Mismatch of the fast bumps resulted from their placement of positions that were not exact multiples of π radians in betatron phase advance. The particles circulated in the program with sinusoidally increasing bumps until all particles were extracted. Figures 6-11 show successive turns at the exit of the electrostatic septa during the extraction process. These plots are for 0.05 mm thick tungsten wire septa, and some beam halo due to scattering by the wires can be seen. The beam is progressively bumped across the wires by two fast bumps. The fast bumps have different amplitudes but the same time dependence B(t), where

$$B(t) \propto \sin(\omega t),$$

and

$$\omega = 1.5 \times 10^5 \text{ r/sec.}$$

The following is a table showing the extraction efficiency for various thickness septa.

THICKNESS	% HITTING 1 MM SEPTUM	% HITTING 15 MM SEPTUM	% SCATTER EXCESSIVELY	TOTAL % LOST
0	4.5 %	0.05 %	0 %	4.55 %
0.05 mm	3.75 %	0.05 %	0.25 %	4.05 %
0.1 mm	3.1 %	0.3 %	1.35 %	4.75 %

The above table indicates that the .05 mm thick septum results in an overall lower loss than the perfect or zero thickness septum. This is the case because the scattering of particles by the wires provides a shield for the 1 mm septum. This scattering, while not resulting in angle large enough to produce beam loss, contributes some emittance blow up to the extracted beam.

Figures 12-14 shows the summation of the extraction turns at 5.76 meters from the downstream end of II-2F quadrupole for 0. mm, 0.05 mm and 0.1 mm thick electrostatic septa, respectively. From these figures the emittance blow up from the finite thickness septa can be seen. The extracted beam emittance is found from these figures to be 5.8 (π)mm·mr or 35 % of the circulating beam emittance.

§3. Bumps for Fast Extraction

The fast bumps for extraction are to be located at I-7F-SS and II-5D-SS. The slow bumps B1, B2, B3, and B4 are to be located at I-7F-SS, I-7D-SS, II-3F-SS, and II-3D-SS, respectively.

A 1 mr radially outward bump at B1 results in the following: a displacement of 14.65 mm and an angle of -2.06 mr at the E.S. septum, and at the extraction channel, a displacement of -1.78 mm and angle of -0.65 mr. This bump can be neutralized by a bend of +0.213 mr at B3 and -1.70 mr at B4.

A 1 mr radially outward (+) bump at B2 results in a displacement of 4.46 mm at the E.S. septum and angle of -0.13 mr. At the extraction septum, this bump produces a 7.51 mm dispalcement and angle of -1.35 mr. This bump can be neutralized by a bend of +0.634 mr at B3 and -0.711 mr at B4.

The electrostatic septum has been placed at +40 mm from the centerline of the beam. This placement is determined by the size of the beam at injection. Due to the large outward excursion of the extracted beam in the II-2F-Quadrupole, the extraction septum has been placed at +20 mm. This will necessitate an injection bump of 20 mm to the inside of the ring. In order to move the edge of a full emittance beam up to the septa, a displacement of 24 mm at the E.S. septum and 4 mm at the extraction septum is required. The required bump strengths to produce X_1 (the displacement at the E.S. septum), and X_2 (the displacement at the extraction septum) can be found from:

$$24 = X_1 = 14.65\ B1 + 4.46\ B2\ ,$$

$$4 = X_2 = -1.70\ B1 + 7.51\ B2\ .$$

Thus

$$B1 = 1.38 \text{ mr} ,$$
$$B2 = 0.852 \text{ mr} .$$

Further,

$$B3 = (0.213)*B1 + (0.634)*B2$$
$$= 0.834 \text{ mr} ,$$
$$B4 = (-1.7)*B1 + (-0.711)*B2$$
$$= -2.95 \text{ mr} .$$

For the case of zero emittance beam the following bump strengths are required.

$$40 = X_1 = 14.65 \text{ B1} + 4.46 \text{ B2} ,$$
$$20 = X_2 = -1.70 \text{ B1} + 7.51 \text{ B2} .$$

Solving,

$$B1 = 1.796 \text{ mr} ,$$
$$B2 = 3.069 \text{ mr} .$$

Therefore

$$B3 = 2.330 \text{ mr},$$
$$B4 = 5.235 \text{ mr} .$$

B4 requires the strongest bend, a bend of 2.25 kG·m. B1 requires a bend of 0.772 kG·m, but must be short to be placed together with the fast bump magnet in the short straight section I-7F-SS. If B1 is 0.2 meters long, it requires a field of 3.86 kG. If B4 is made 0.60 meters long, it will require a field of 3.75 kG.

The fast bump at II-5D-SS has more stringent requirement of the two fast bumps since it is after a defocusing quadrupole, and must be 1.73 times as strong. A bump of 1.05 mr from the fast bump at I-7F-SS will displace one-half of a full emittance beam across the wires of the E.S. septum, a displacement of 18 mm, which is adequate for multi-turn fast ejection. Using 1.25 mr for the strength of the I-7F-SS fast bump, it can be seen that II-5D-SS bump must produce a 0.928 kG·m bend, or a field strength of 1.85 kG for a one-half meter long fast bump magnet.

From the following relations,

displacement at E.S. septum = 14.65 B1 + 4.46 B2

and displacement at Ext. septum = -1.70 B1 + 7.51 B2, algorithms can be made using the multiples of the four bumps to provide displacement at one septum without changing the position at the other septum. These algorithms can be helpful in tuning the system to minimize beam loss. In this system, however, although the beam position at one point may be unaffected, the angle at that point must change. In order to provide another degree of freedom in setting up the system, it will be necessary to provide remote positioning control for the E.S. septa, 1 mm septum, and the 15 mm septum.

In the following table, a beam of emittance 16.6 (π) mm·mr was used to calculate the alignment of the E.S. septa and the thin magnetic septa. These positions can be found using the effect of the slope of the emittance, the slow bumps, the fast bumps, the bend strengths of the element, and the effect of II-2D-quadrupole. Form the computer program, the angle of the emittance due to the fast bumps was found to be -2.4 mr and the angle due to the slow bumps is -2.83 mr. The position of the E.S. septa was found by additing $\frac{1}{4} \phi_{ES} \ell^2$ to the position of the septa which was determined by the initial angle. ϕ_{ES} is the bend/meter of the septa, and 1 is the distance along the septa.

DEVICE	DISTANCE INTO STRAIGHT SECTION	HORIZONTAL DISPLACEMENT (Indicates Center of Septum Plane)
Upstream End of E.S. Septum	0.85 meters	40.00 mm
at 1 meter into E.S. Septa	1.85 meters	34.89 mm
at 2 meter into E.S. Septa	2.85 meters	30.01 mm
Downstream End of E.S. Septum	3.85 meters	25.37 mm
1 mm Magnetic Septum		
Upstream End	4.15 meters	24.01 mm
Downstream End	5.24 meters	18.99 mm
3 mm Magnetic Septum		
Upstream End	After Def. Quad. +0.9 meters	19.30 mm
Downstream End	After Def. Quad. +1.7 meters	20.96 mm

§4. Extraction Channel

The angle of the circulating beam at the entrance to the extraction channel is due to the slope of the beam envelope and the effect of the slow bumps. This angle is −4.28 mr. The most inside extracted particles are located at +36.21 mm with an angle of −6.21 mr. Thus the extracted beam is separated from the circulating beam by 16.21 mm and has a convergent angle of 1.93 mr.

Figure 15 shows a layout of II-2F long straight section. The first magnet is a 15 mm thick septum magnet which has a field of 8 kG and is 1.5 meters in length. The second magnet is a 35 mm septum magnet. It is 1.2 meters in length and has a field of 16 kG. The third magnet also has a field of 16 kG, but this magnet may have a septum thicker than 35 mm. This magnet is 1.56 meters in length.

The following table indicates the horizontal position of these magnets and their distance from II-2F-quadrupole. The horizontal displacement number indicates the edge of the septum adjacent to the air gap of the extractor magnets. At 5.46 meters into the straight section the innermost extracted particles are displaced from the beam centerline by 272.18 mm and have an outward angle of 120.54 mr.

DEVICE	DISTANCE INTO STRAIGHT SECTION	HORIZONTAL DISPLACEMENT (Indicates Inside Edge of Septum Coil)
15 mm Magnetic Septum		
Upstream End	0.8 meters	35.00 mm
Downstream End	2.3 meters	
35 mm Magnetic Septum		
Upstream End	2.4 meters	50.25 mm
Downstream End	3.6 meters	80.00 mm
Thick Magnetic Septum (>35 mm)		
Upstream End	3.7 meters	90.00 mm
Downstream End	5.26 meters	240.00 mm

§5. Conclusion

Shaving extraction can be a viable system for fast extraction of the 12 GeV proton beam. Using the foregoing design, an efficiency of 96 % can be achieved. At a later date the installation of pulsed quadrupoles to increase β_H at the extraction system could raise the efficiency even higher. Shaving extraction results in a smaller emittance than a single turn fast extraction and is readily applicable to bunched or debunched beams.

The hardware for the shaving extraction system closely resembles that of a slow extraction system and would require little modification to provide slow spill beam or even slow and fast beam simultaneously.

Thus this system appears to be the best choice for the fast extraction from KEK PS.

Acknowledgement

The authors wish to thank Prof. Hajime Yoshiki and the people of the KEK Computer Center for all their help.

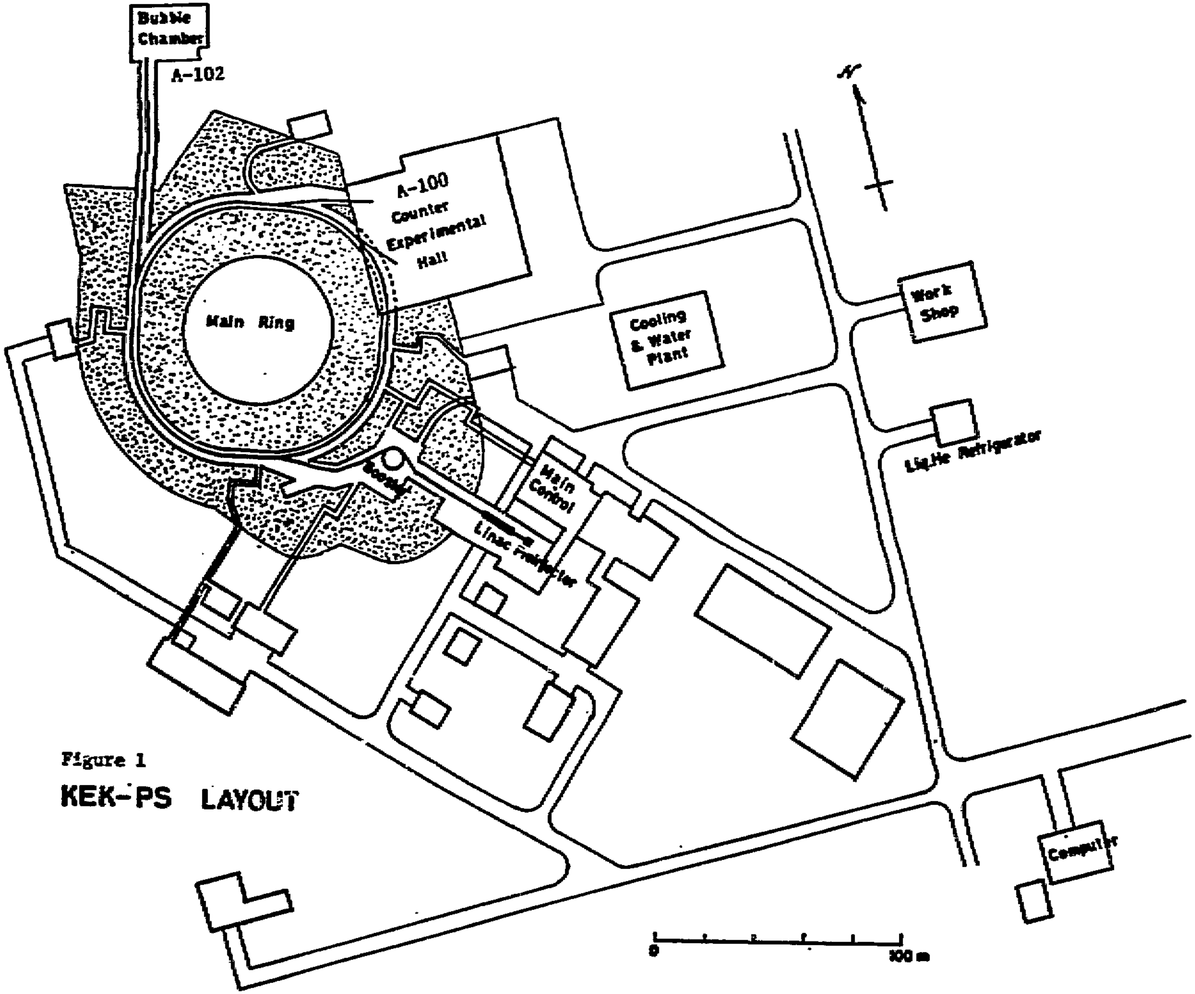


Figure 1

KEK-PS LAYOUT

I1F	Q MAG. for SLOW EJ.
I1F	SEPTUM MAG. for INJ.
I2F	KICKER for INJ.
I7F	BUMP for FAST EJ.
I7F	FAST BUMP for FAST EJ.
I7D	BUMP for FAST EJ.
II1F	E.S. SEPTUM for FAST EJ.
II1F	SEPTUM MAG. for FAST EJ.
II1D	SEPTUM MAG. for FAST EJ.
II2F	EXT. MAG. for FAST EJ.
II3F	BUMP for FAST EJ.
II3D	BUMP for FAST EJ.
II5F	OCT. MAG. for SLOW EJ.
II5D	FAST BUMP for FAST EJ.
II7F	BUMP for SLOW EJ.
II7D	BUMP for SLOW EJ.
III1F	E.S. SEPTUM for SLOW EJ.
III1F	SEPTUM MAG. for SLOW EJ.
III1D	SEPTUM MAG. for SLOW EJ.
III2F	EXT. MAG. for SLOW EJ.
III3F	BUMP for SLOW EJ.
III3D	BUMP for SLOW EJ.
III5F	INTERNAL TARGET
IV1F	RF CAVITY
IV2F	RF CAVITY
IV3F	Q MAG. for SLOW EJ.

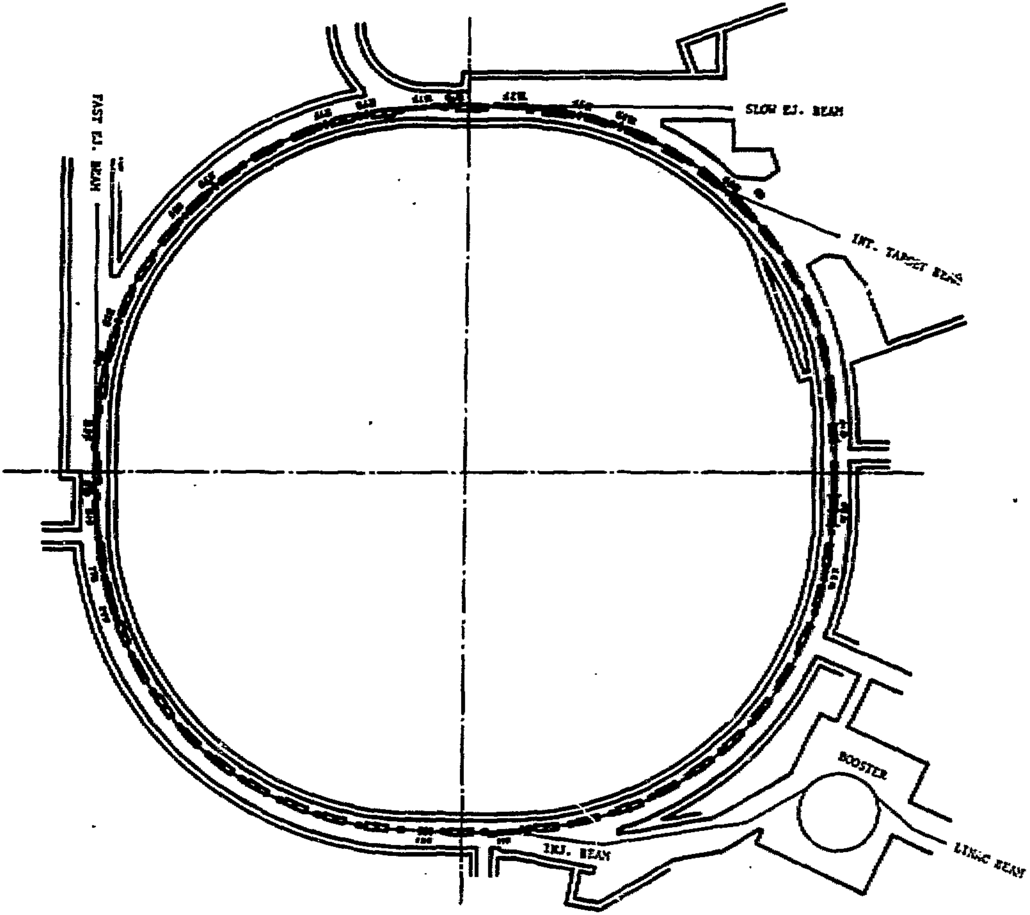


Figure 2

KEK 12 GeV MAIN RING

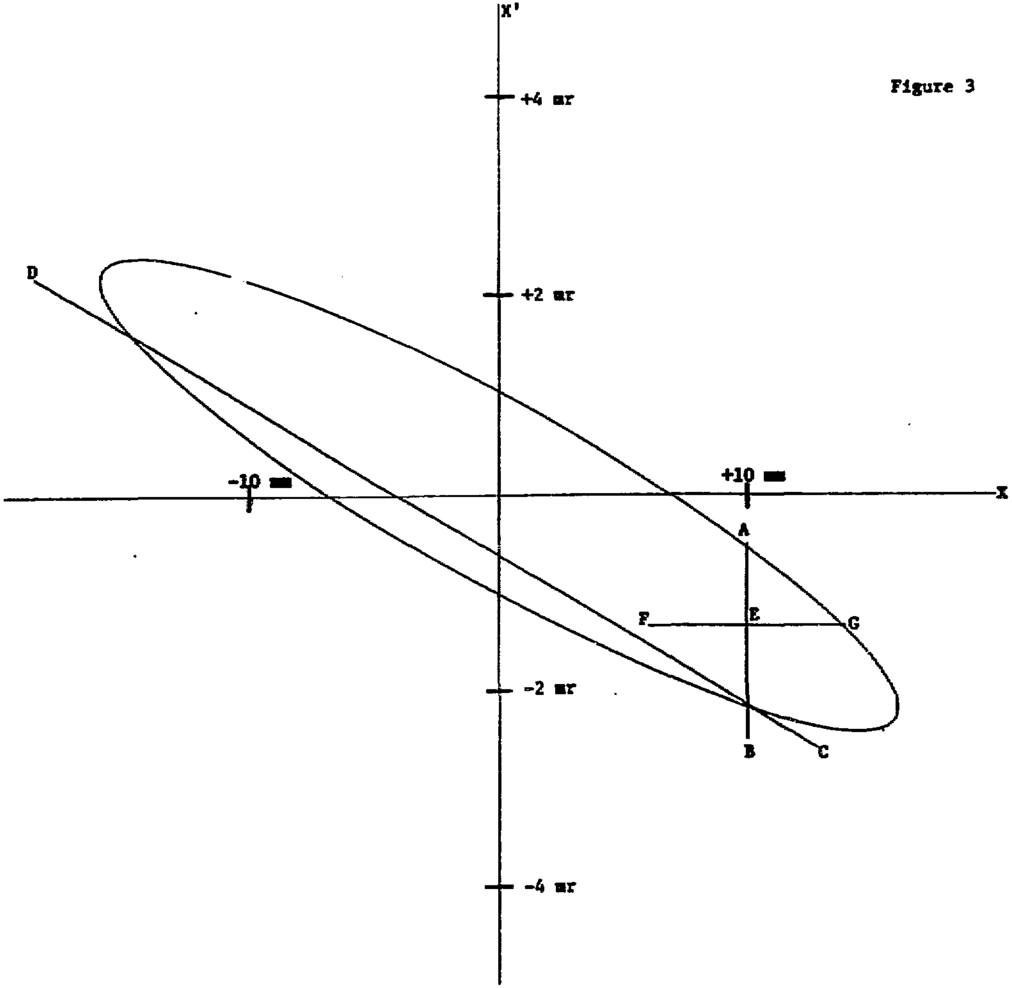
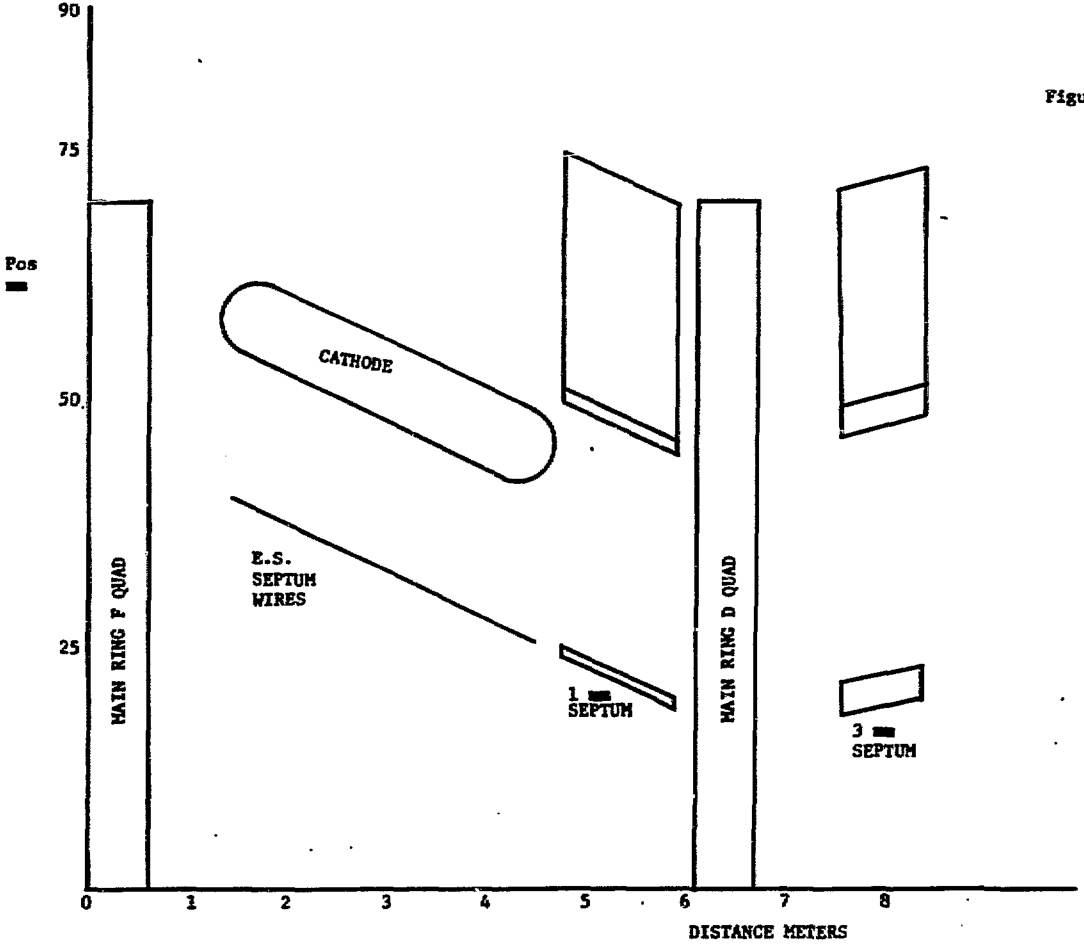


Figure 3

Figure 4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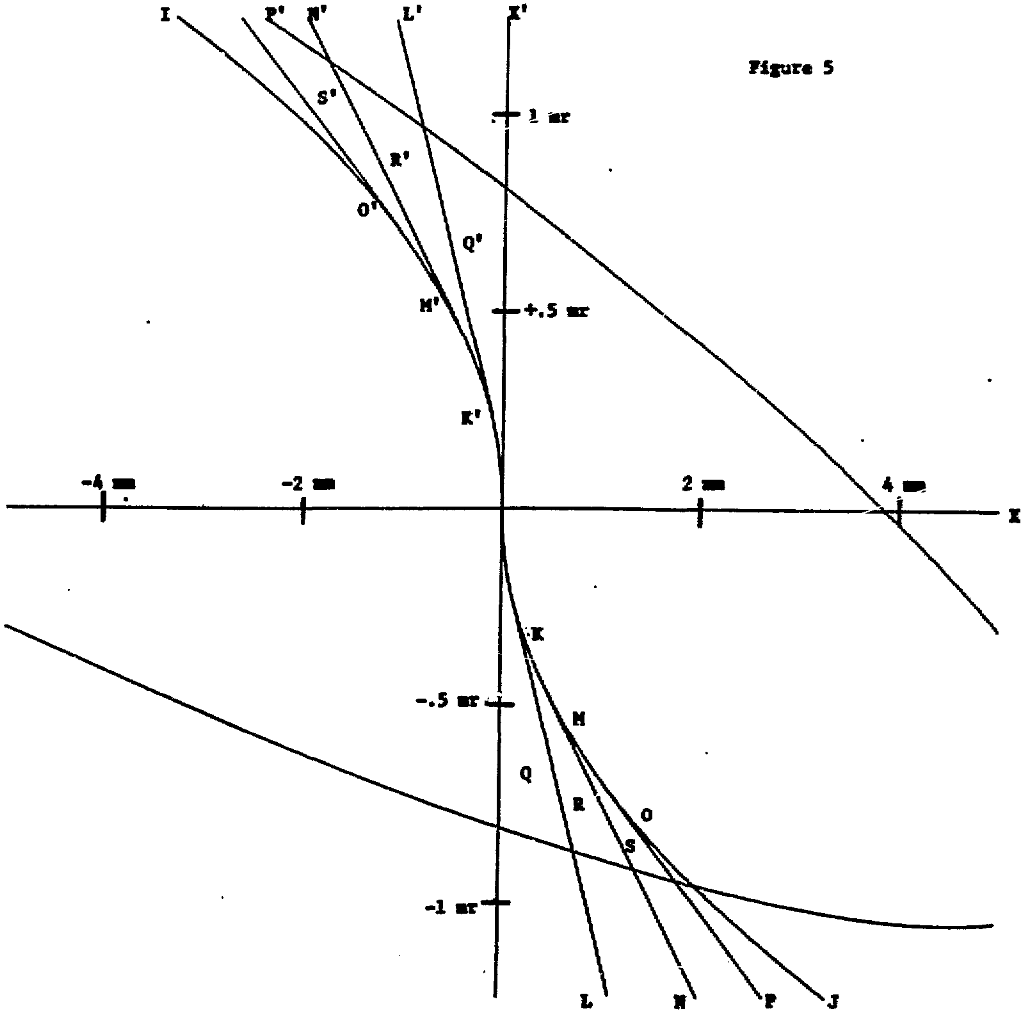
8
DISTANCE METERS

Figure 5



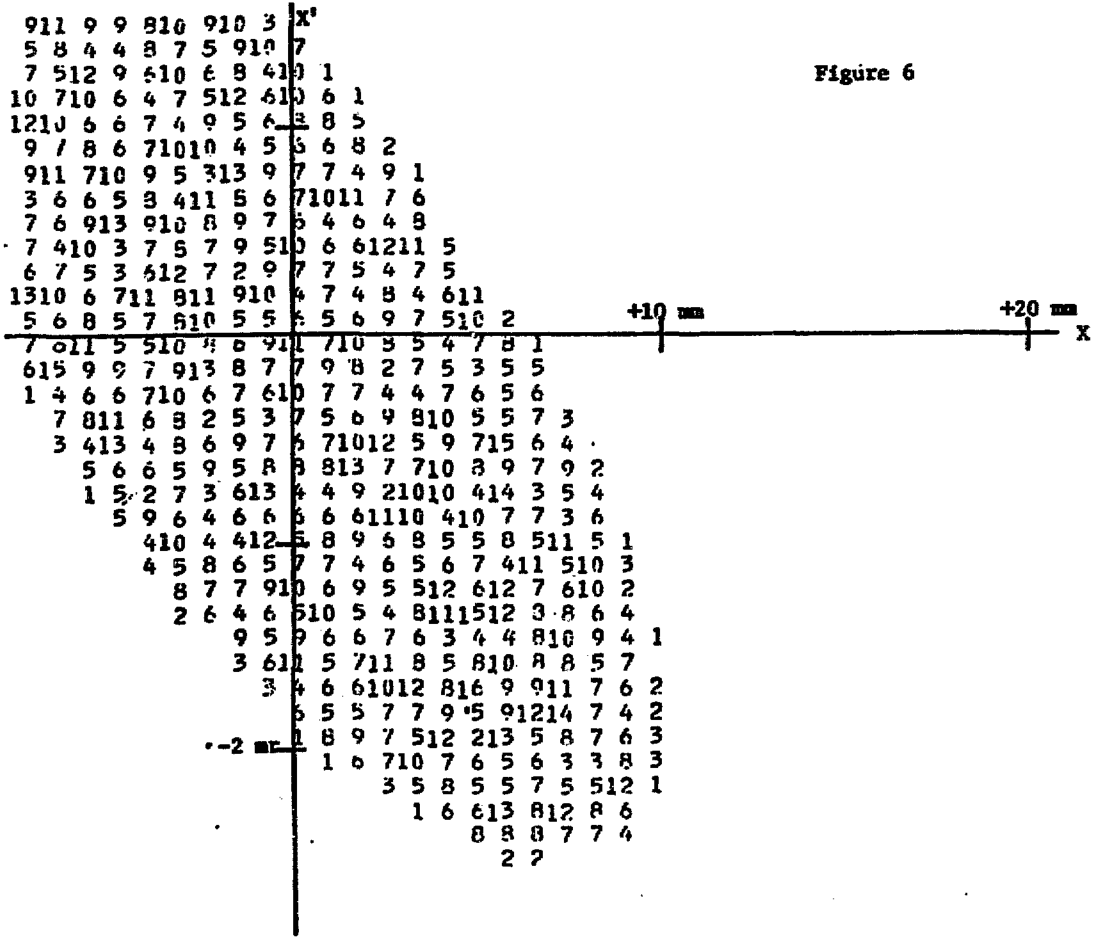


Figure 6

Figure 7

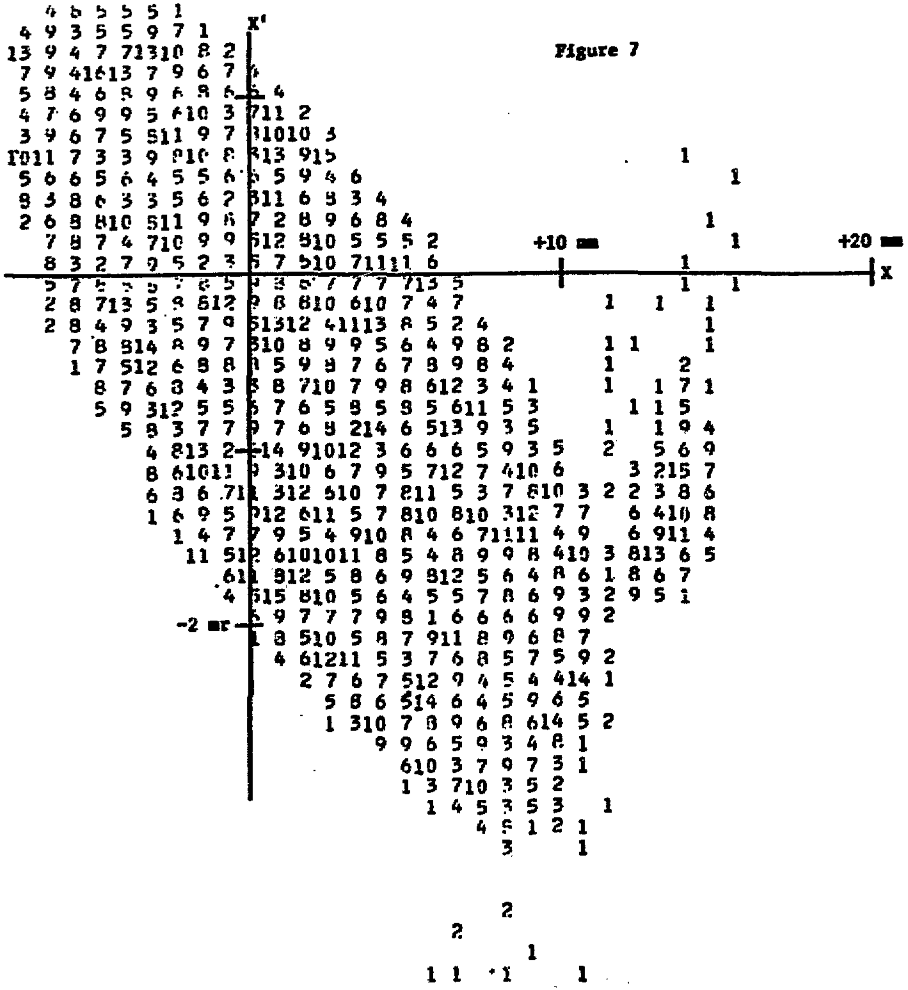
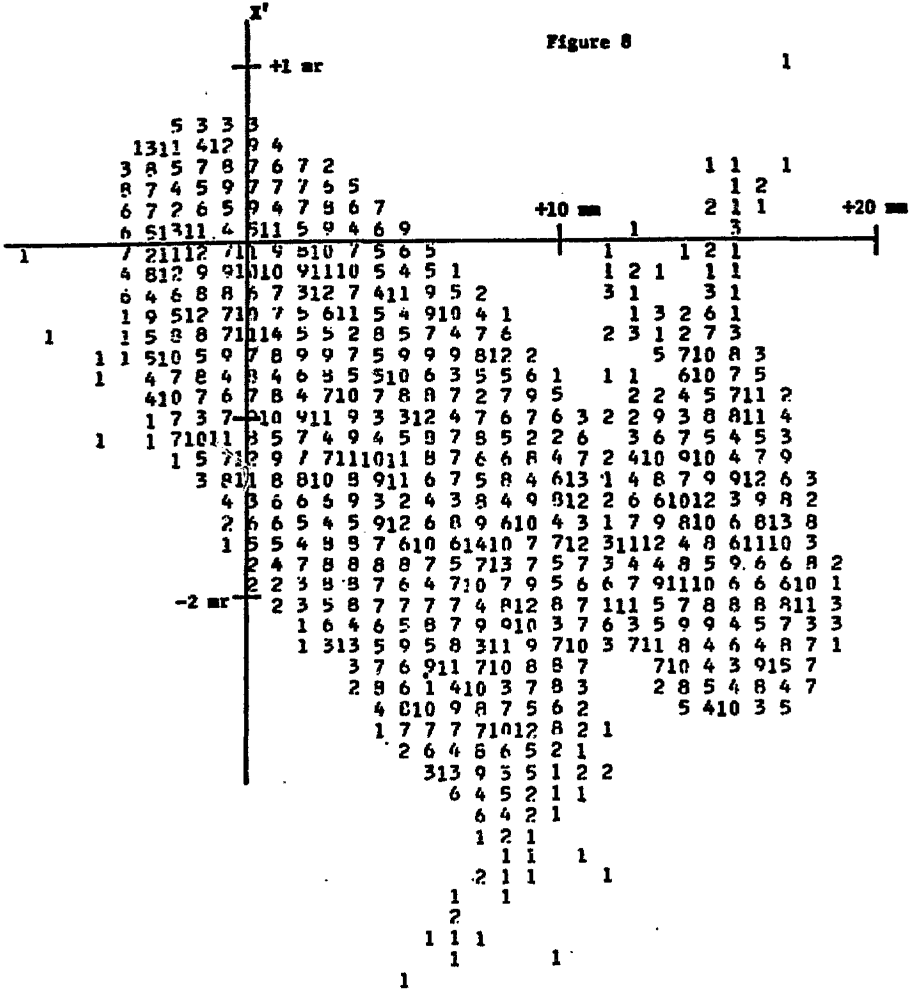


Figure 8



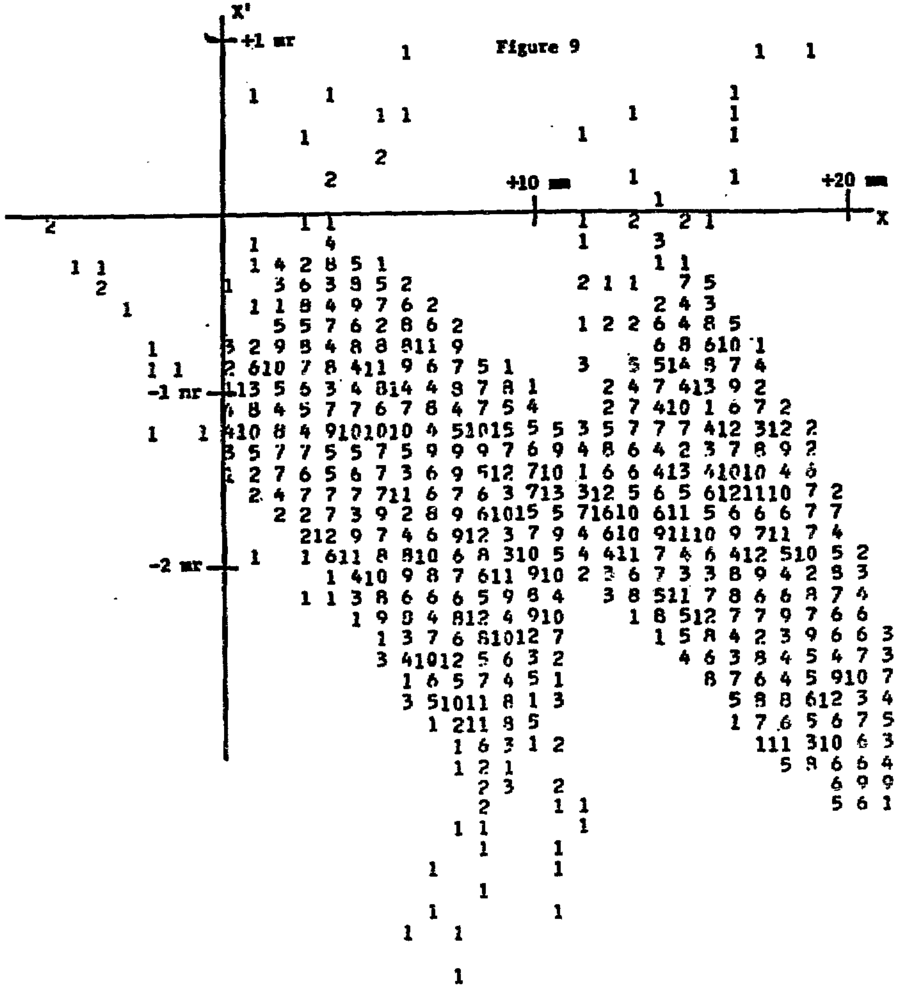


Figure 9

Figure 10

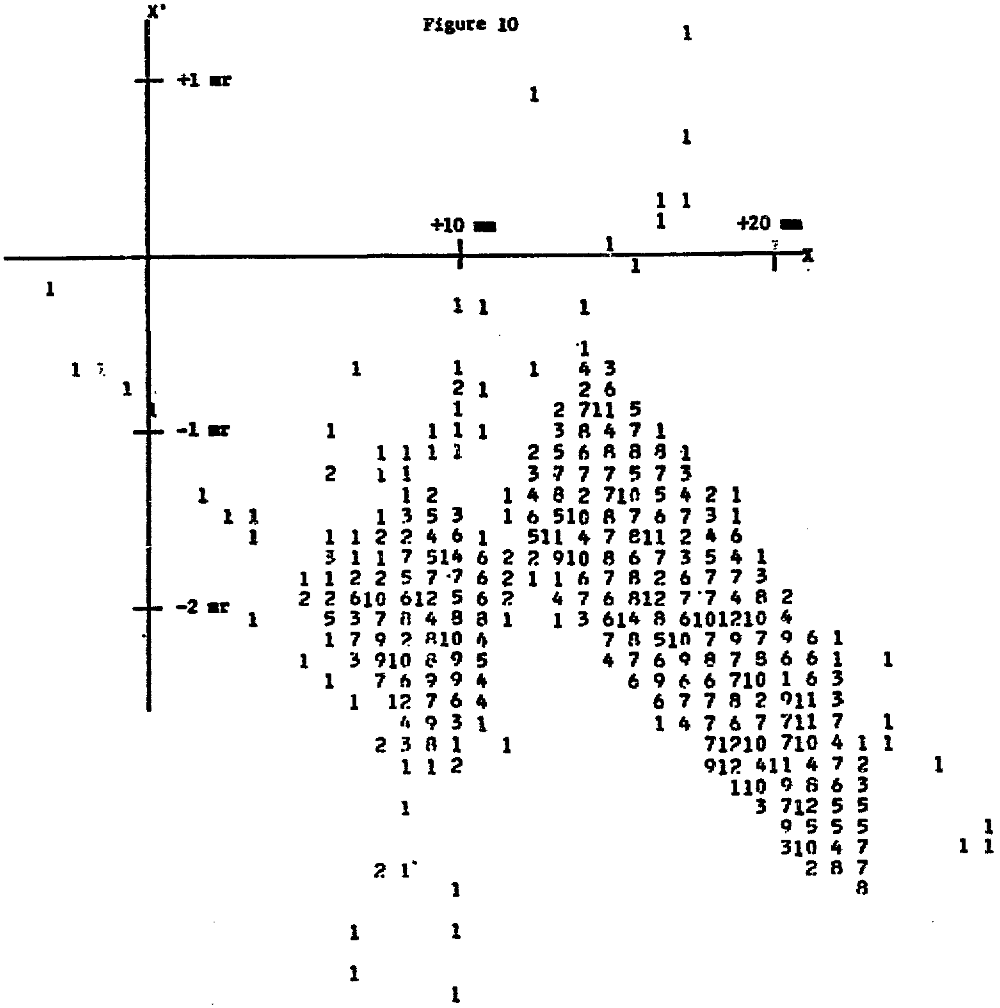
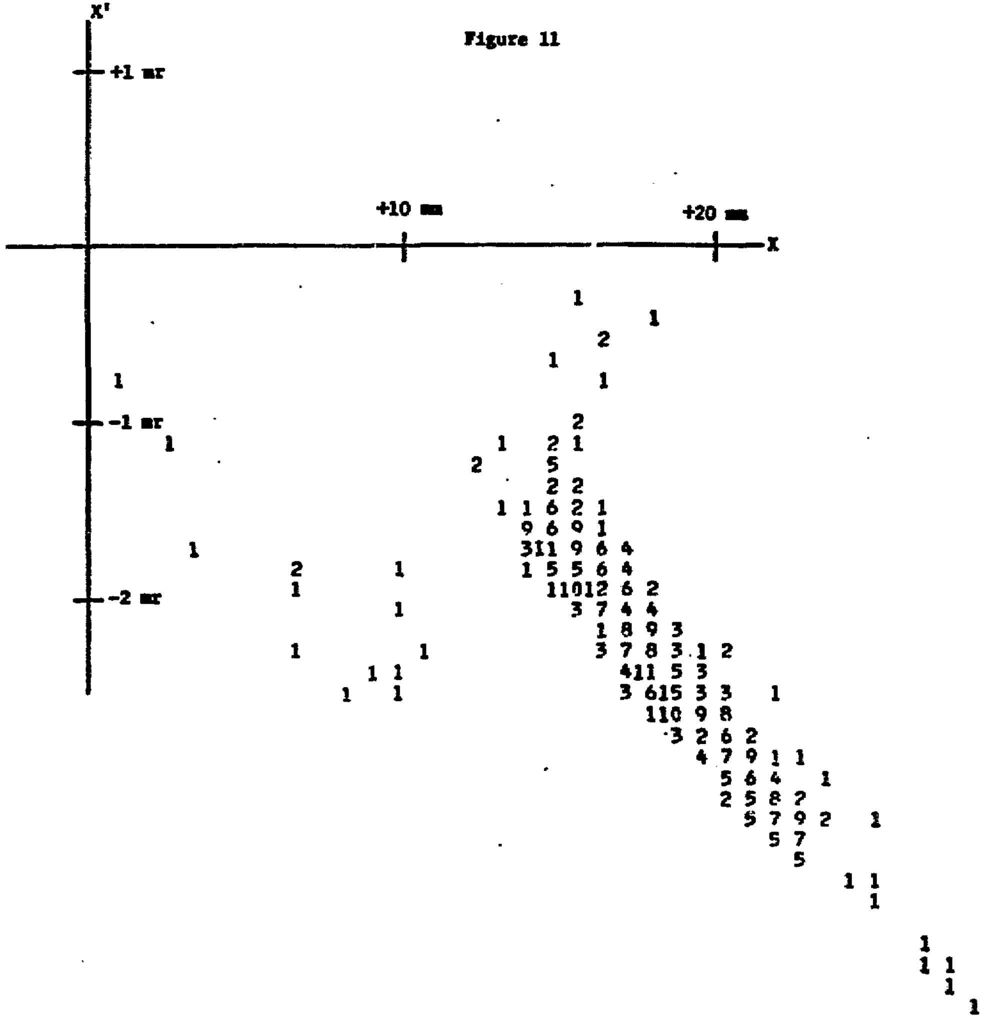


Figure 11



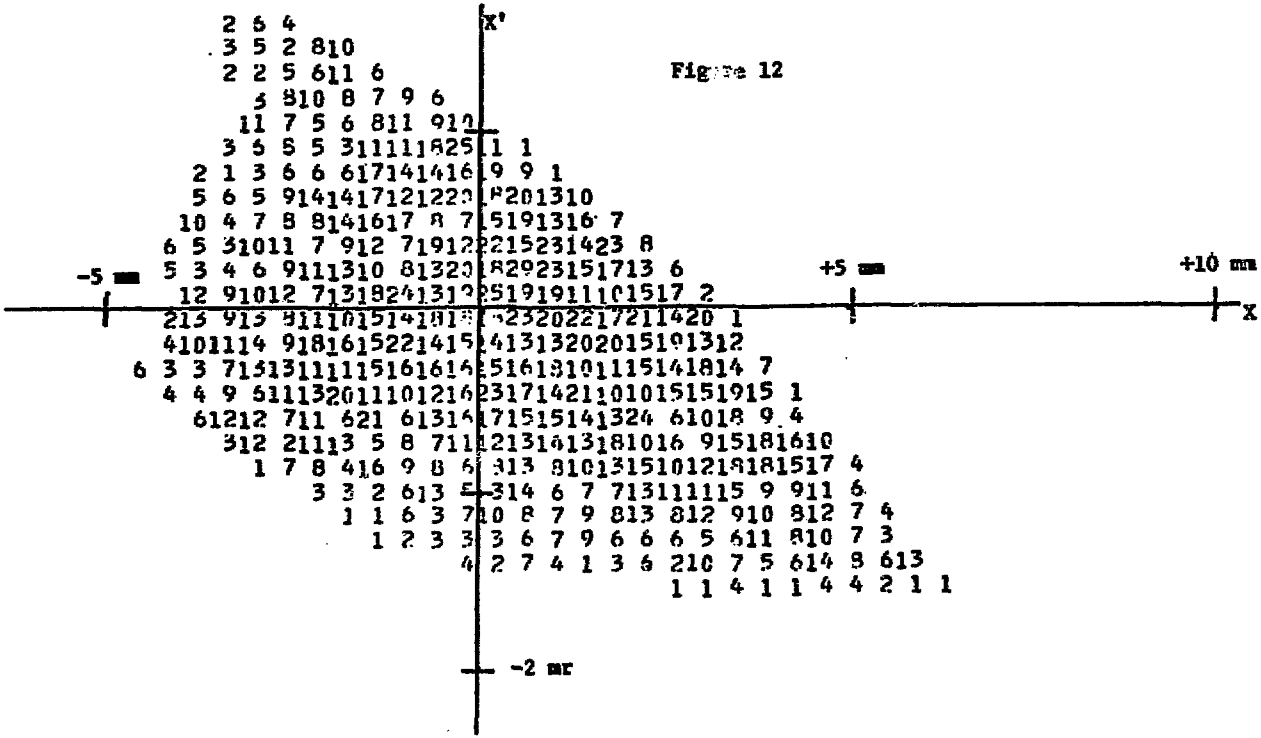


Figure 12

Figure 13

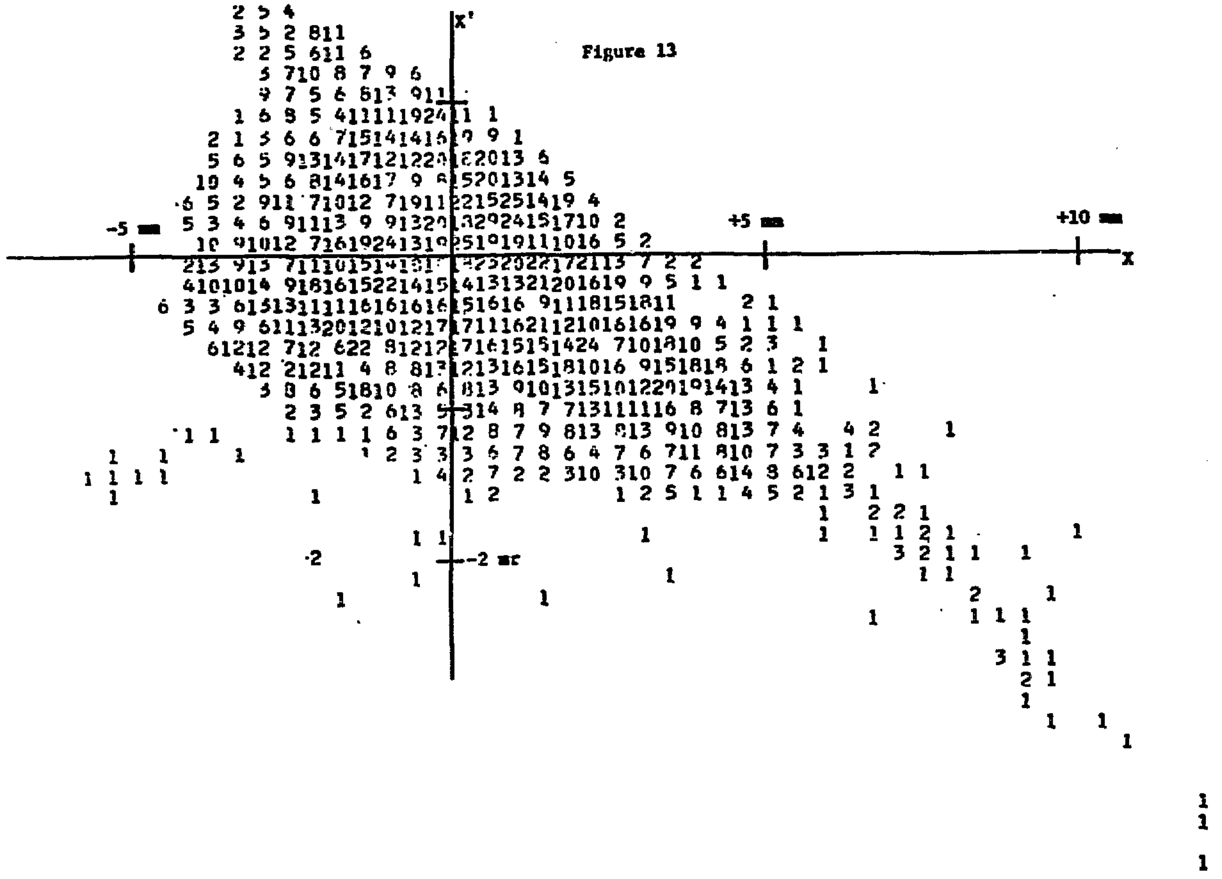
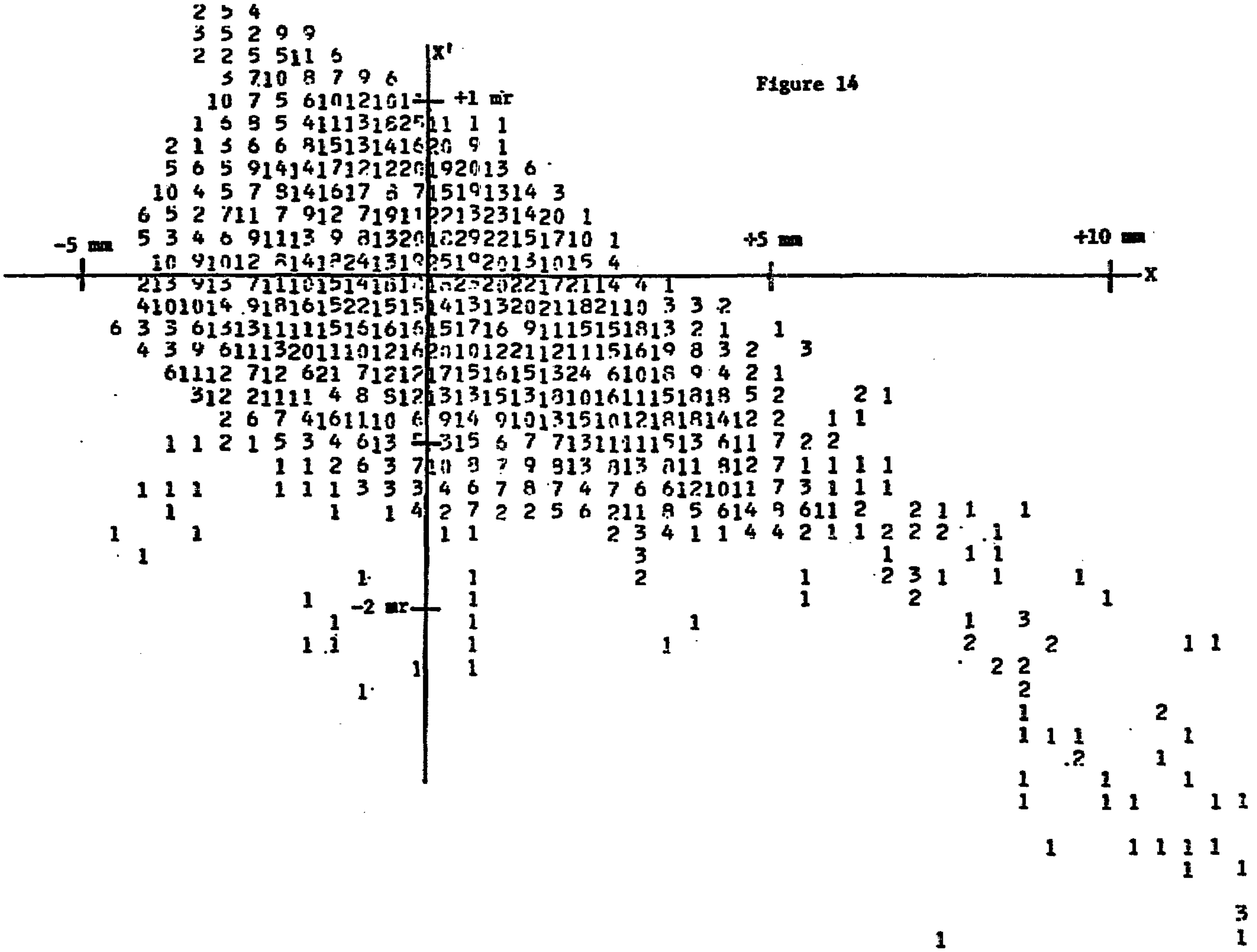


Figure 14



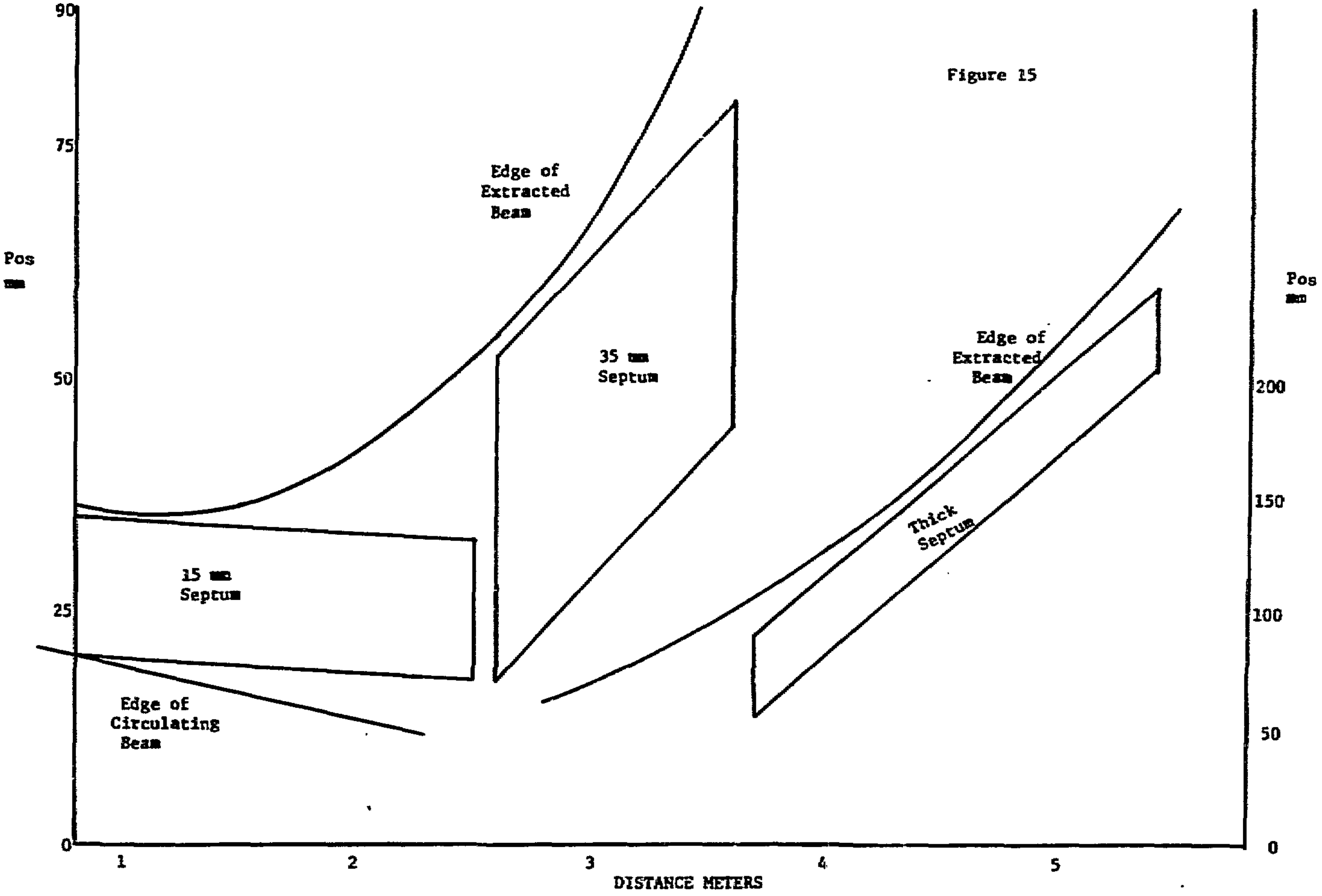


Figure 15
90
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DISTANCE METERS