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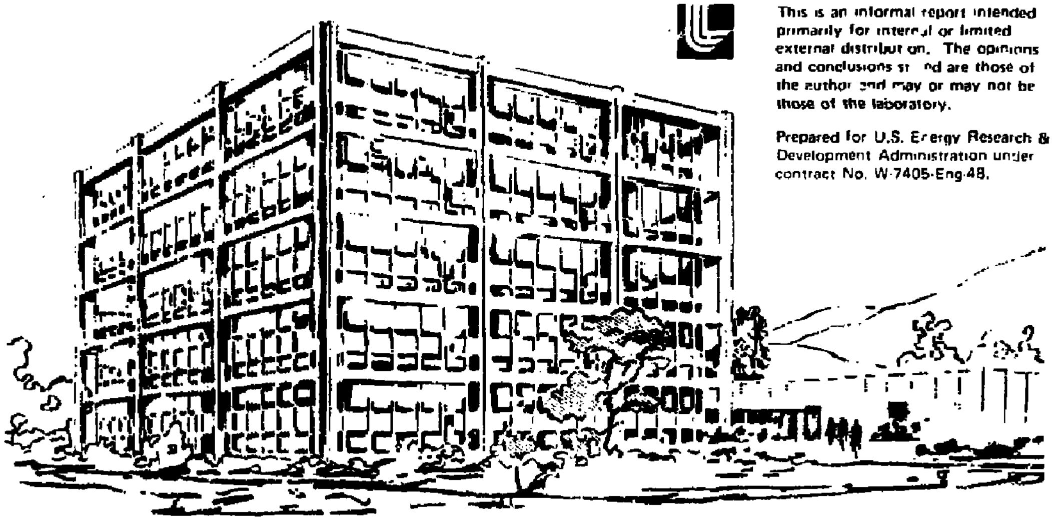

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SUMMARY

A series of drift-surface and magnetic-field calculations has been carried out to try to estimate the accuracy with which the elements of the TMX magnet set must be magnetically aligned. The results of these calculations, for 500 G at the solenoidal center, are summarized here.

One might think that the misalignment of the magnet elements could distort the curvature of the magnetic-field lines in the solenoidal section sufficiently so that radial drifts of the trapped ions, and even radial losses, could occur. Radial shifts indeed take place. But the calculations show that the drift surfaces of ions magnetically trapped in the solenoidal section are an insensitive indicator of misalignment problems. The intersections of these drift surfaces with the solenoidal midplane tend to remain closed and shift with respect to the solenoidal axis by an amount comparable to or less than the misalignment shifts of the plugs and transition Cees.

The more sensitive measure of the required alignment accuracy is the position of a drift surface at a plug midplane calculated for ions that pass through the solenoid and reflect at the outer mirror regions of the plugs,

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or, similarly, the mapping along magnetic-field lines of the plasma cross section at the solenoidal midplane to a plug midplane. The solenoidal plasma should map to the region of the plug plasma so that ions escaping from the solenoid can be reflected by the plug plasma potential. If we use as the criterion that a 31-cm-radius circle at the solenoidal midplane (representing the plasma there) should map into an approximate circle (with about 7-cm radius) at a plug midplane with center shifted by not more than 1.0 cm from the plug magnetic axis, then a plug set and the corresponding pair of transition Cees must be aligned with respect to one another to within about 0.5 cm. The combination of the plug set and transition Cees, when well aligned with respect to one another, can be misaligned with respect to the solenoidal axis by a considerably larger amount and still satisfy our criterion.

An additional observation made during the series of drift-surface calculations reported here is that we must guard against slight dips in $|B|$ in the nearly uniform solenoidal magnetic-field region. Such magnetic-field fluctuations can temporarily trap ions with pitch angles near 90°, which in turn can cause the particles to drift radially and be lost. A smoothing of the solenoidal magnetic field eliminates this problem.

DRIFT SURFACES OF IONS IN THE SOLENOIDAL SECTION

For reference, three views of the TMX[1] current-carrying magnet elements are given in Figs. 1 through 3. Figure 1 shows a 3-D perspective, Fig. 2 shows the projection on the x-z plane, and Fig. 3, the projection on the y-z plane. The currents used in these elements for the calculations presented here are discussed in the final section of this report.

Figures 4 through 8 show, for various misalignment configurations, the intersection with the solenoidal midplane (at $z = 0$) of several drift surfaces calculated for D^+ ions magnetically trapped in the solenoidal section. (These ions do not enter the plugs, but reflect before reaching the inner-mirror maximum of each plug.) The assumed misalignments involve moving the elements of a plug set (baseball coil plus two nested Cees) as a unit or moving a pair of transition Cees as a unit in a direction perpendicular to the TMX magnetic axis. Two or more misalignments are used in each example.* Table 1 summarizes numbers pertinent to these calculations and results.

When we refer to a drift-surface plot, we mean the intersection of the particular calculated drift surface with a plane perpendicular to the magnetic (z) axis, usually the solenoidal midplane. Each point plotted is a pass of the ion through that plane, moving either in the positive or negative axial direction as indicated by the symbols. The starting point

*In all the results presented in this report, the origin of the coordinate system remains at the center of the solenoidal section, with the z axis always being the axis of the solenoid. Thus the displaced coil elements have their centers at nonzero values of x or y.

and direction of precession are shown in each figure. A guiding-center calculation is used to follow the ion trajectories.[2] The drift surfaces shown in this report are a representative sample of the many calculated during the misalignment investigations.

Figures 4 through 6 show drift surfaces for a pitch angle of 87^{o} at the solenoidal midplane. In all three cases, the shift of the drift surface at the solenoidal midplane is in the direction of the misalignment of the plugs and of magnitude comparable to (greater than, in Fig. 6) the misalignment. (With no misalignment, the drift surface is centered on the z axis.) The misalignment is exaggerated in Fig. 6, causing the curvature of the solenoidal field lines to be changed enough that the ion starts out at 31 cm drifting opposite to the normal precession-drift direction. (The normal direction of the ∇B precession drift is clockwise, corresponding to $\vec{B}$ pointing in the +z direction and the magnitude of the magnetic field acting on the ion decreasing with increasing radius, on the average.) Even though there is radial drift in Fig. 6, the drift surface is still closed, its center of precession having shifted a considerable distance out radially.

Figures 7 and 8 show drift surfaces for a pitch angle near the loss cone. The particles reflect in the vicinity of the transition Cees rather than closer to the solenoidal midplane as in the large-pitch-angle calculations. The same misalignments are assumed in Fig. 7 as in Fig. 5, and in Fig. 8 as in Fig. 4 (see Table 1). A comparison of the two plots constituting each pair shows that the intersection of the calculated drift surface with the solenoidal midplane changes with pitch angle for a given set of misalignments. That is, there is not omnigenity, at least for the relatively large misalignments assumed.

We used an ion energy of 320 eV for the large-pitch-angle calculations instead of the usual 80 eV in order to speed up the calculations. The precession-drift rate tends to be slower for the large-pitch-angle ions because they remain in an almost uniform magnetic field. The higher energy increases the precession rate and thus reduces the computer time needed to follow a particle for a given number of precession periods without changing the resulting drift surface. The value of 320 eV is in the range of the maximum ion energy expected to be confined by the plug plasma potential.

The drift-surface examples presented here suggest that radial loss arising from any reasonably expected misalignment in TMX (expected to be considerably less than 5 cm) should not be a problem. In toroidal magnetic confinement, the curvature of the field lines can cause drifts to the wall, and thus particle losses, because the center of curvature of the field lines is outside the vacuum chamber. In TMX, although misalignment of magnetic elements can change the curvature of the field lines, the center of curvature still should remain well inside the solenoidal volume. Thus, the ions precess around the new center, maintaining closed drift surfaces.

MAPPING THE SOLENOIDAL PLASMA TO THE PLUGS

It is important in a tandem-mirror experiment that the plasma area at the solenoidal midplane projects along magnetic-field lines to a region at a plug midplane filled with plug plasma so that ions trying to escape from the solenoid are reflected by the plug plasma potential. This requirement proves to be a sensitive restriction on the allowable misalignment of TMX magnet elements.

Figure 9 shows an example of this sensitivity. Plotted there are the intersections of a drift surface with the midplanes of the two plugs for an ion that passes through the solenoid and reflects at the outer mirrors of the plugs. The ion was started at $r = 31$ cm, $\theta = 0^{0}$ in the solenoidal midplane. The misalignments assumed here: -z plug moved 1.0 cm in the +x direction, pair of -z transition Cees moved 1.0 cm in the -x direction. The calculated drift surface is nearly centered (to within 0.5 cm) on the plug (and solenoidal) axis at the +z end, where there is no magnet-element misalignment. But, at the -z end, the drift-surface center is shifted about 3.6 cm from the solenoidal axis in the -x direction, or 4.6 cm from the center of the displaced plug. Assuming the plug plasma to be located mainly within a radius of 7 cm at the plug midplane, we observe that a sizable fraction of the solenoidal-plasma area (i.e., that area encompassed by the calculated drift surface) does not project to the region of plug plasma. And we are considering only 1.0-cm misalignments here, not those of 5.0 cm as in the last section.

We can obtain almost the same results as in Fig. 9 by mapping a 31-cm circle centered on the solenoidal axis at the solenoidal midplane (representing the plasma there) along magnetic-field lines to the plug midplanes. This field-line calculation takes less computer time than the corresponding drift-surface calculation. The results of this calculation for the misalignments of Fig. 9 are shown in Fig. 10, and are seen to be almost the same as those in Fig. 9. Because of this equivalence, most of the rest of the misalignment results presented in this section are obtained from mapping along magnetic-field lines. This mapping gives a good approximation to the drift-surface calculations because the axis of each drift surface is close to the solenoidal axis at the solenoidal midplane (somewhat shifted because of the assumed misalignments) and because a radial distance is reduced when moving from the solenoidal midplane to the plug midplane (e.g., 31-cm radius reduces to 7 cm).

As an example, Fig. 11 shows the intersection of the drift surface of Fig. 9 with the solenoidal midplane. The lack of closing of the curve after one precession period may be calculational. Even if it were a real radial drift, it is a small shift considering the 8-ms time the particle was followed (expected total ion lifetime is about 25 ms). The drift-surface center appears displaced from the solenoidal center by no more than 1.4 cm. This reduces at the plug midplane to a radial length of about 0.3 cm, a relatively small correction. Also, any deviation of the drift-surface shape in Fig. 11 from the circle used in the mapping along magnetic-field lines is less than an ion gyroradius, so is within acceptable limits of our accuracy.

Table 2 and Fig. 12 summarize the results from the calculations of mapping along magnetic-field lines. Various sets of small misalignments were assumed, and the resulting displacements at the plug midplanes of the projected solenoidal plasma obtained. Figure 12 gives the numbers of Table 2 in visual format.

The first entry in the table and figure corresponds to the configuration of Fig. 10, while the second entry is like the first except the magnet-element misalignments have been decreased by a factor of four. The resulting mappings to the plugs for the decreased-misalignment case are shown in Fig. 13, and are to be compared with Fig. 10 with its larger misalignments. The portion of the projected solenoidal plasma that does not overlap the plug plasma is much reduced in Fig. 13 compared with Fig. 10, with a shift of only a little over 1 cm with respect to the plug axis. This appears more acceptable experimentally. This ≈ 1-cm criterion for the acceptable maximum displacement of the mapped area corresponds to a distance of about one-third gyroradius for a mean-energy (26 keV) plug ion with all energy in the perpendicular direction at the plug midplane.

We now compare the results of the different types of misalignments assumed. We see that misalignments perpendicular to the plane of the field-line fan of the transition-Cee pair and plug inner mirror (i.e., in the x direction at the -z end) have a bigger effect in distorting the mapping (Entry A) than do misalignments parallel to that plane (Entry C). This occurs because of the way the field lines fan outward in the x-z plane as one moves from the region of the transition Cees to the -z plug midplane. Entry D shows that when both the plug and transition Cees are displaced together in the same direction (e.g., +x at the -z end) the center of the mapped circle moves by almost the same amount and in the same direction. The uniformity of the large solenoidal region allows all the magnet elements at an end of TMX to move together without greatly affecting the mapping. The final entry (E) involves displacements at both ends of TMX. Only the results at the +z end are plotted in Fig. 12 because the -z misalignments are the same as in Entry A, and the decoupling between the two ends (observed in Fig. 10) permits about the same results at the -z end as in Entry A. Of the varied examples in Table 2 and Fig. 12, the largest nonoverlapping of the mapped solenoidal plasma and the plug plasma is found for Entry A, where the plug and transition-Cee pair are moved in opposite directions, perpendicular to the plane of the field-line fan of the transition-Cee pair and plug inner mirror.

Although most of the calculations summarized here used 500 G at the solenoidal center, on one occasion we checked the sensitivity to misalignment at 2 kG, also. The misalignments assumed are those of Fig. 10, and the coil currents used are those obtained from earlier optimization calculations. The results are similar to those in Fig. 10 except that a 31-cm-radius circle at the solenoidal midplane now maps into circles of approximately 14-cm radius at the plug midplanes, with about a 4.5-cm shift of the center at the -z plug instead of 3.6 cm as in Fig. 10.

This study of the sensitivity of the field-line mapping to various types of misalignment is certainly not exhaustive in scope. We have shifted the three elements of each plug as a unit, and each pair of transition Cees as a unit. In a continuance of this investigation, one could shift the magnet elements within a group with respect to one another, and also could shift the octupole elements. Small shifts in the large solenoidal elements should have little effect. Various magnet elements could also be tilted with respect to the solenoidal magnetic axis.

DIPS IN THE SOLENOIDAL REGION

For many of the calculations in the misalignment investigations, we used a set of currents in the magnet elements that gives a magnetic field in the solenoidal region uniform in $|B|$ to 10% over a 1.9-m axial length centered on the midplane. No great effort was expended to avoid small dips (or ripples) in $|B|$ in this region, which can arise from the use of a discrete number of current elements. As long as we followed ions with pitch angles near the loss cone, the effect of any dips was small because the ions quickly passed through them.

But, when we began to look at pitch angles near 90^{o}, where the ions reflected in the almost uniform central region, the effect of dips became noticeable. Figure 14 shows an example of the problem that arose, even with all the magnet elements aligned. As with many of the other figures in this report, Fig. 14 shows the intersection of a calculated drift surface with the solenoidal midplane. The starting point and direction of precession are again shown. The gaps at 45^{o} and each 90^{o} interval thereafter occur when the ion becomes temporarily trapped in a slight (about 20 G out of 500 G) $|B|$ depression away from the midplane region. It stays in that depression for a number of reflections, until it precesses aximuthally enough to escape. It then moves back through the midplane and is again plotted. This alternation between being caught in an off-midplane dip and passing through the midplane after each reflection continues as the ion precesses aximuthally around the magnetic axis.

A problem arises because there are components of $\vec{B}$ associated with the dips that can cause the ion to drift radially while it is temporarily trapped in a dip. Some radial drifting can be observed in the first 1 1/3 precession periods in Fig. 14. After that, the radial drifting begins to dominate, the overall drifting becomes erratic, and the particle is soon lost. This ion is lost in 4.4 ms, a time short compared with the expected total ion lifetime of about 25 ms, but long compared with the time for scattering through a large angle, i.e., a fraction of a ms. The scattering should reduce the adverse effect of the dips.

By adjusting the currents in some of the magnet elements, we have smoothed out the magnetic field and improved the regularity of the drift surfaces. Figure 15 shows a drift surface after the field smoothing, for the same particle conditions as in Fig. 14. This revised magnetic field is uniform in $|B|$ to 10% over an axial length of only 1.2 m, now. We can probably produce a longer uniform field that does not have dips. The example used here is to show that smoothing the dips can eliminate the undesirable radial drifts. (The drift surfaces of Figs. 4 through 8 were calculated using the smoother field of Fig. 15. Figures 7 and 8 are not changed much by the smoothing.) The magnet-element currents used before and after the smoothing are summarized in Table 3.

ACKNOWLEDGMENT

Helpful discussions with Grant Logan concerning these investigations are acknowledged and appreciated.

REFERENCES

1. TMX Major Project Proposal, LLL-Prop-148, January 12, 1977.

2. W.A. Perkins and D. Fuss, MAFCO II - A Code for Calculating a Guiding Center Trajectory of a Particle in Magnetic and Electric Fields, Lawrence Livermore Laboratory Rept. UCRL-50438 (1968).

TABLE 1. Summary of numbers pertinent to the drift-surface calculations shown in Figs. 4 through 8.

Fig.	Misalignment of coil elements				Pitch angle at midplane (deg)	Starting radius at midplane (cm)	D^+ energy (eV)	Characteristics of drift surface at solenoidal midplane	
	-z		+z						
	Plug (cm)	Trans.Cees (cm)	Plug (cm)	Trans.Cees (cm)				Position of center (cm)	Approximate radius (cm)
4	x=+5	0	x=+5	0	87	31	320	x=+5, y=0	26
5	x=+5	x=-5	y=+5	x=+5	"	"	"	x=+3.5, y=+3.5	27
6	x=+25	x=+15	x=+25	x=+15	"	"	"	x=+43, y=0	10
7	(same as Figure 5)				9.5	"	80	x=+4, y=0	27
8	(same as Figure 4)				"	"	"	x< 1, y=0	31

TABLE 2. Summary of calculations for mapping of 31-cm-radius circle at solenoidal midplane, centered on the solenoidal axis, to both plugs, for various misalignment configurations (and comparisons with drift-surface calculations).

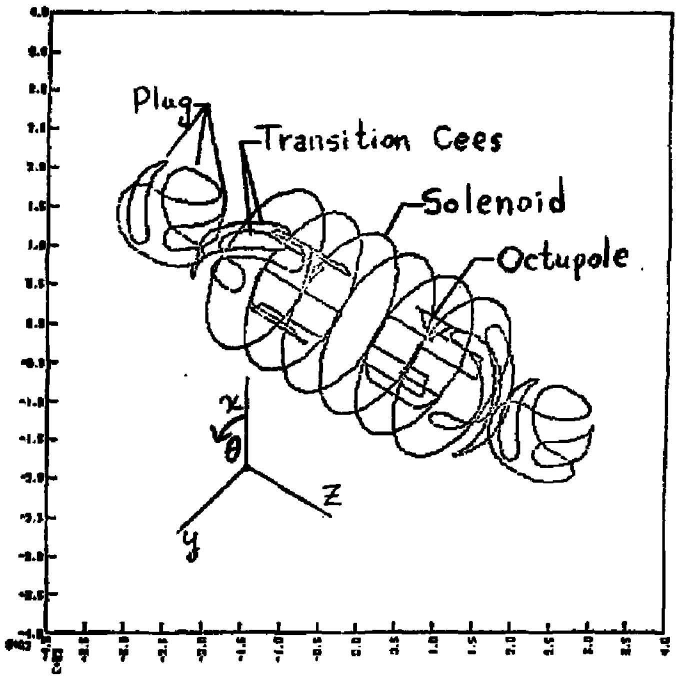
Entry	Fig.	Misalignment of coil elements				Center of mapping to plug midplane of 31-cm-radius circle at solenoidal midplane†		Center of calculated drift surface at plug midplane†	
		-z		+z					
		Plug (cm)	Trans.Cees (cm)	Plug (cm)	Trans.Cees (cm)	-z (cm)	+z (cm)	-z (cm)	+z (cm)
A	10	x=+1.0	x=-1.0	0	0	x=-3.5	x=-0.05	x=-3.6	x=-0.5
B	13	x=+0.25	x=-0.25	0	0	x=-0.86	x= 0.00	(not calculated)	
C	-	y=+1.0	y=-1.0	0	0	y=+0.8	y=+0.2	y=+0.74	y=+0.1
D	-	x=+1.0	x=+1.0	0	0	x=+0.85	x=-0.02	x=+0.9	x=+0.1
E	-	x=+1.0	x=-1.0	y=+1.0	x=+1.0	x=-3.4	y=-1.4	(not calculated)	

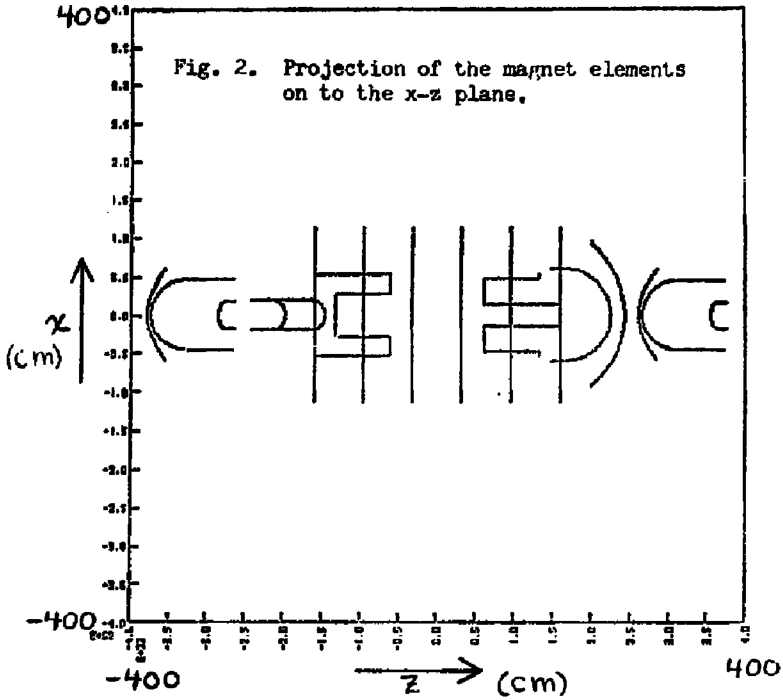
†Where x or y displacements are not given, they are exactly or nearly zero.

TABLE 3. Magnet-element currents used for the misalignment calculations (500 G at center of solenoid).

Magnet element	Current used (for one-turn element) (kA)	
	Before smoothing (Figs. 9-14)	After smoothing (Figs. 4-8, 15)
Solenoidal-coil loops at z =		
± 32 cm	32.8	25.0
± 96 cm	- 0.5	unchanged
±160 cm	- 60.0	- 30.0
Octupoles	8.3	unchanged
Transition Cees:		
Inner	118.5	150.0
Outer	138.7	unchanged
Plug Cees:		
Inside	385.0	"
Outside	457.0	"
Baseball Coils	1478.0	"

Fig. 1. 3-D perspective of current-carrying magnet elements used in misalignment calculations. The origin of the coordinate system is at the center of the solenoid.




400
Fig. 2. Projection of the magnet elements on to the x-z plane.
x
(cm)
-400
-400
z
(cm)
400

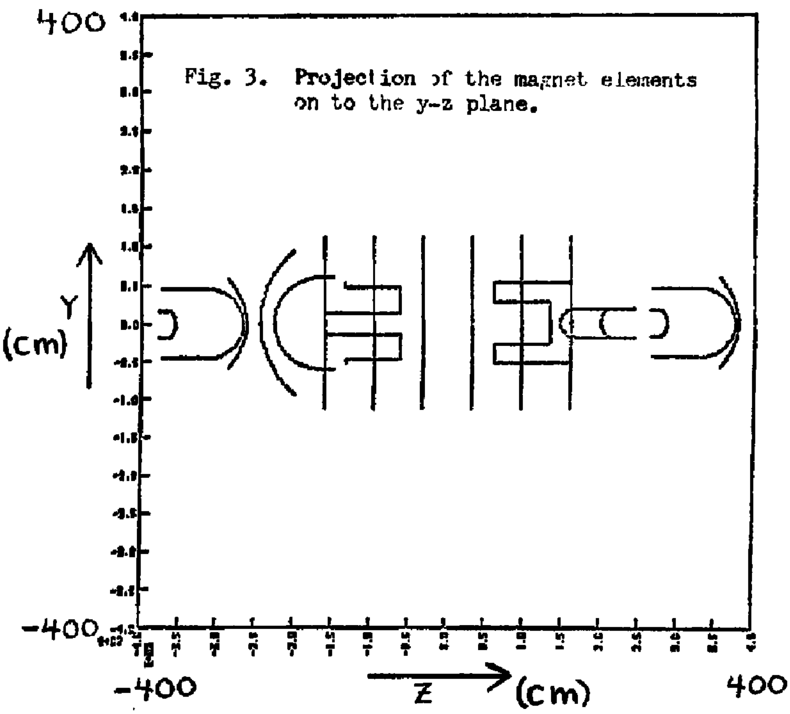

400
Fig. 3. Projection of the magnet elements on to the y-z plane.
Y
(cm)
-400
-400
z
(cm)
400

Fig. 4. Intersection of calculated drift surface with solenoidal midplane for both plugs shifted 5 cm in +x direction, and 87° pitch angle (at the solenoidal midplane). The starting point and direction of precession are shown.

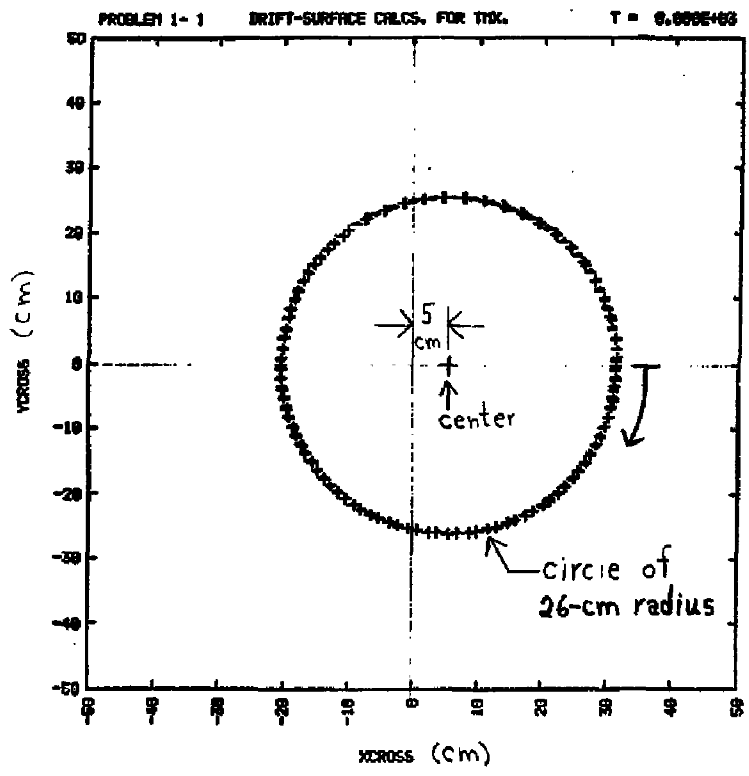


Fig. 5. Drift surface at solenoidal midplane for both plugs and both pairs of transition Cees moved 5 cm in either the x or y directions (see Table 1), and 87° pitch angle.

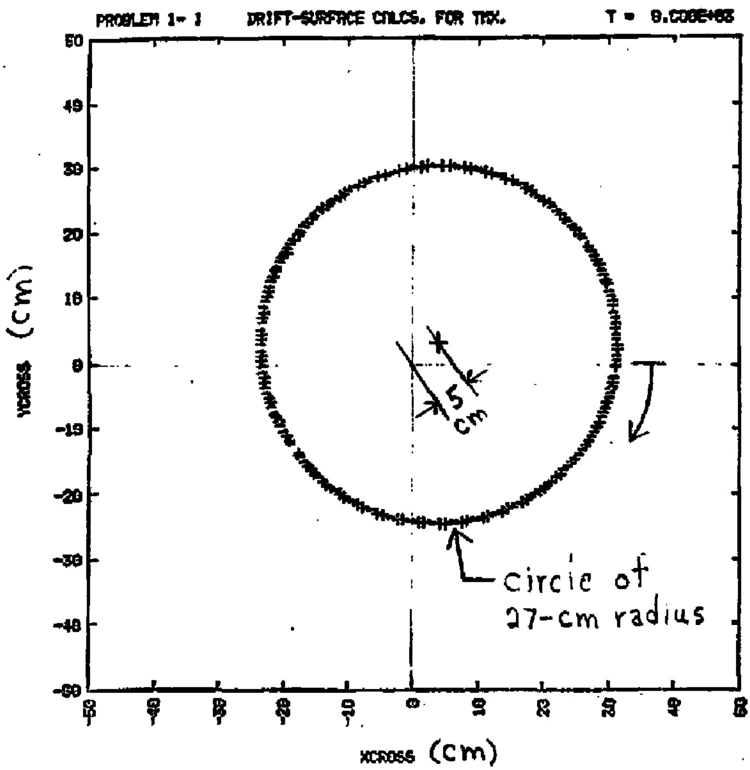


Fig. 6. Drift surface at solenoidal midplane for both plugs moved 25 cm in the +x direction and both pairs of transition Gees moved 15 cm in +x direction, and 87° pitch angle.

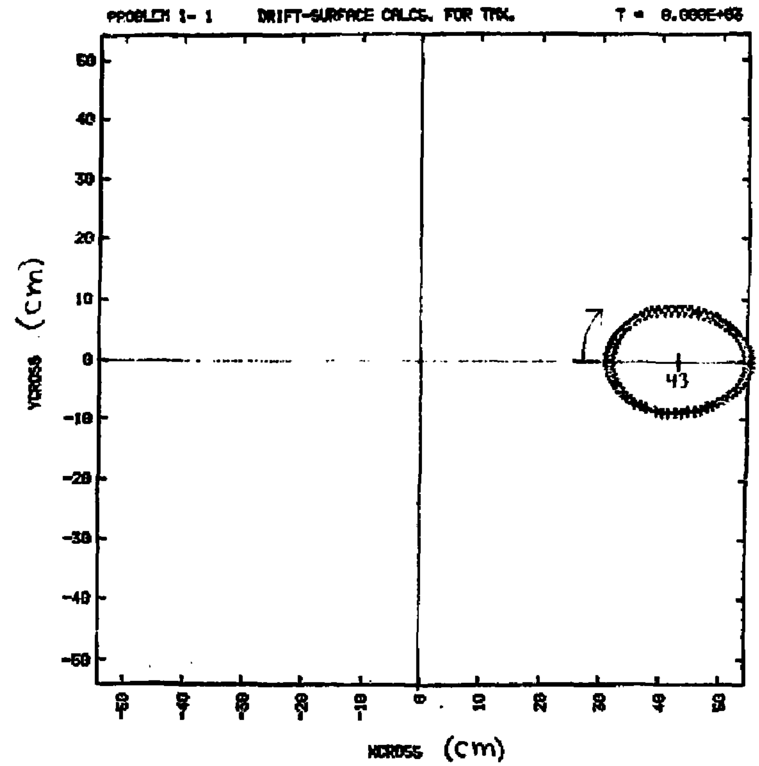


Fig. 7. Same as Fig. 5 except pitch angle at solenoidal midplane is now 9.5° instead of 87° (and D^+ energy is 80 eV instead of 320 eV). The ± symbols refer to the sign of the axial velocity at the midplane.

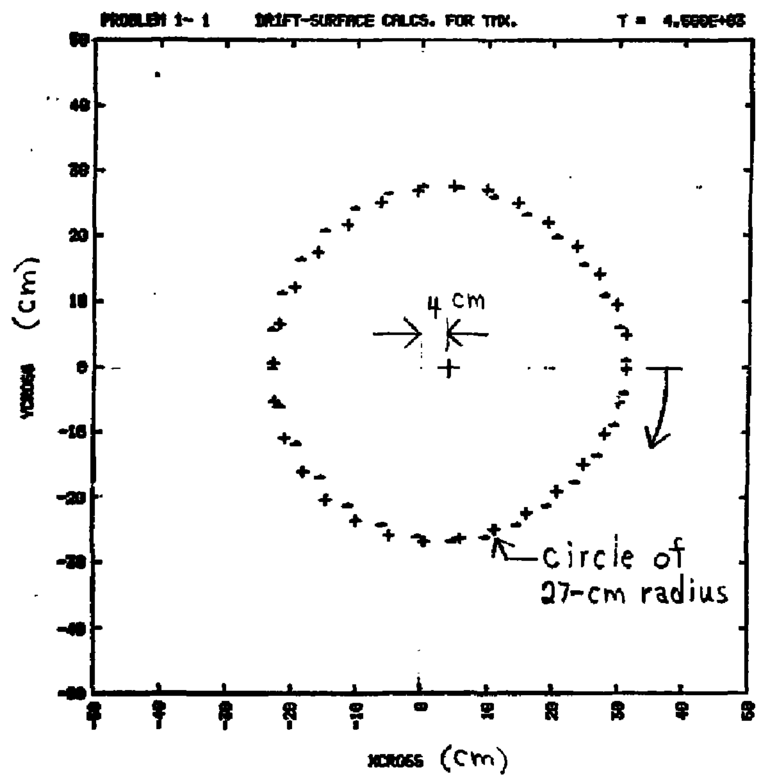
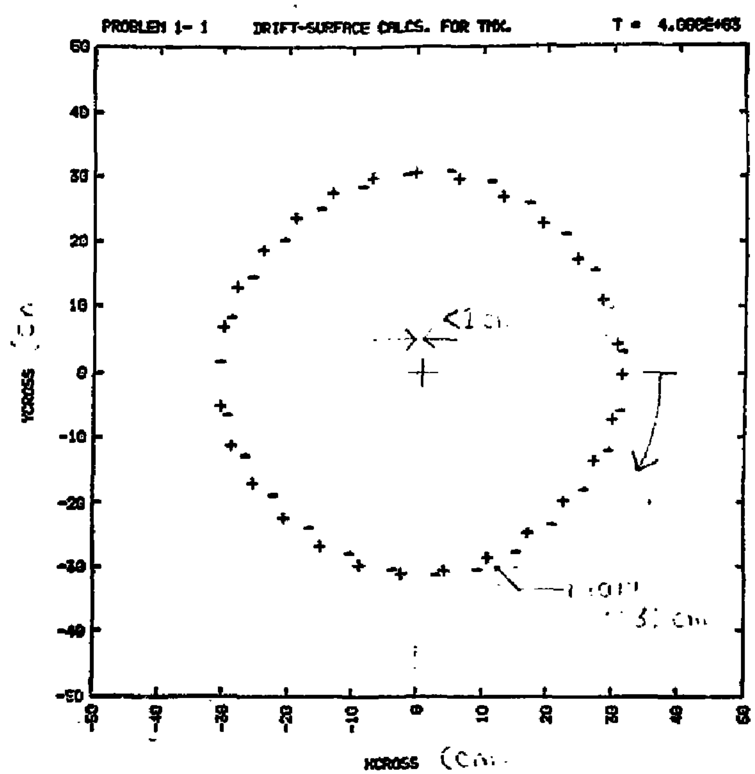


Fig. 8. Same as Fig. 4 except pitch angle is now 9.5° and energy is 80 eV.



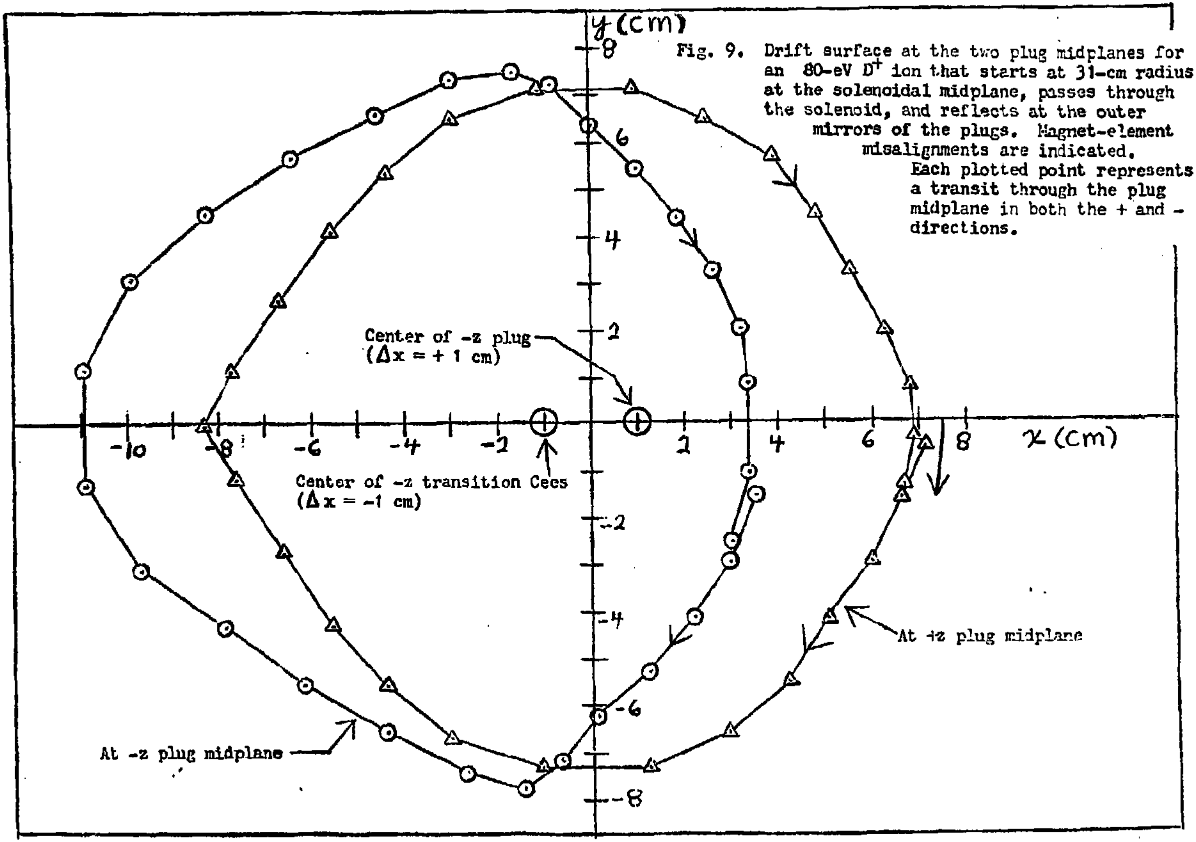


Fig. 9. Drift surface at the two plug midplanes for an 80-eV D^+ ion that starts at 31-cm radius at the solenoidal midplane, passes through the solenoid, and reflects at the outer mirrors of the plugs. Magnet-element misalignments are indicated. Each plotted point represents a transit through the plug midplane in both the + and - directions.

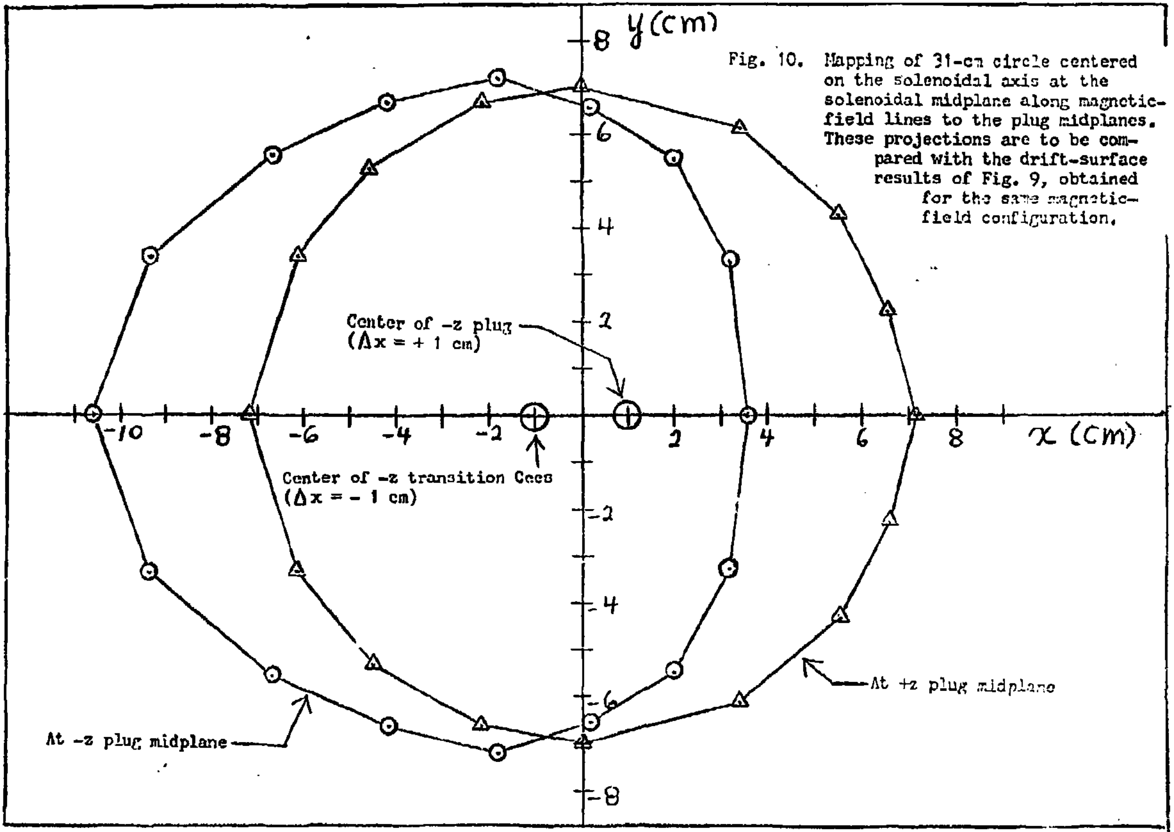


Fig. 10. Mapping of 31-cm circle centered on the solenoidal axis at the solenoidal midplane along magnetic-field lines to the plug midplanes. These projections are to be compared with the drift-surface results of Fig. 9, obtained for the same magnetic-field configuration.

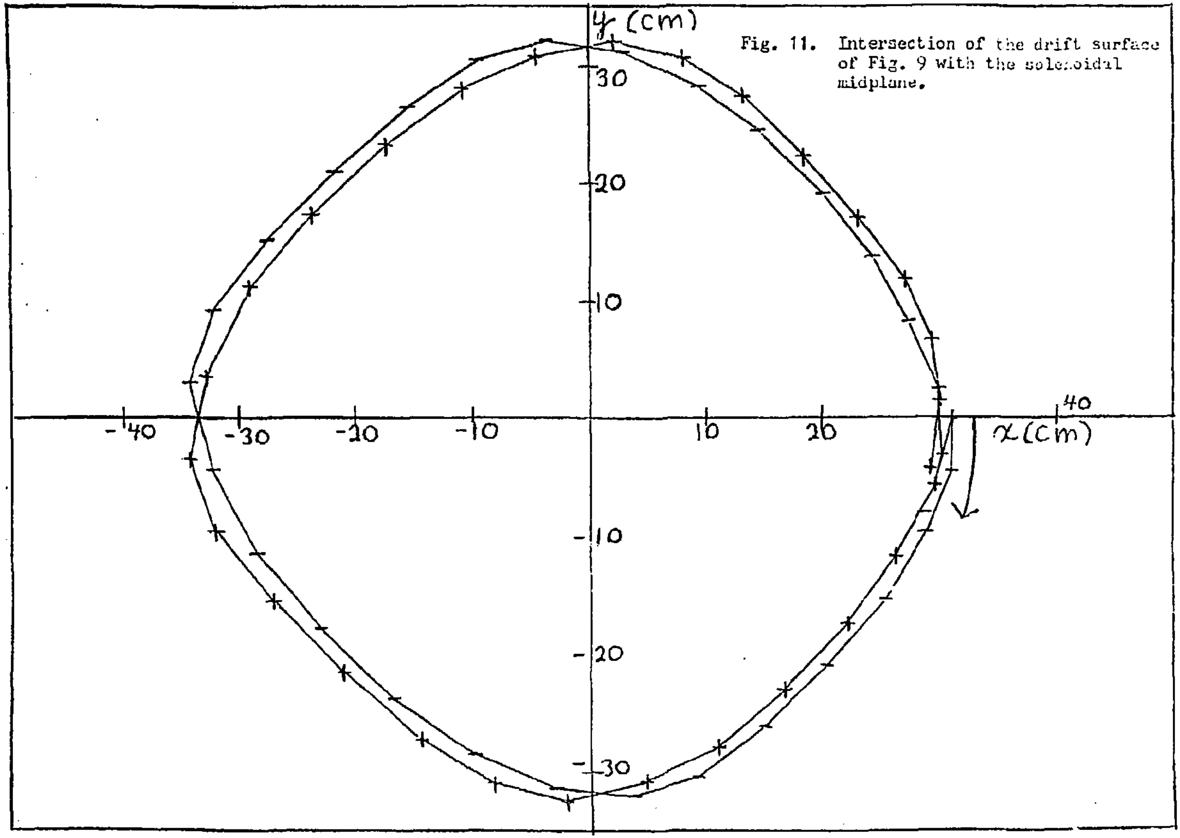
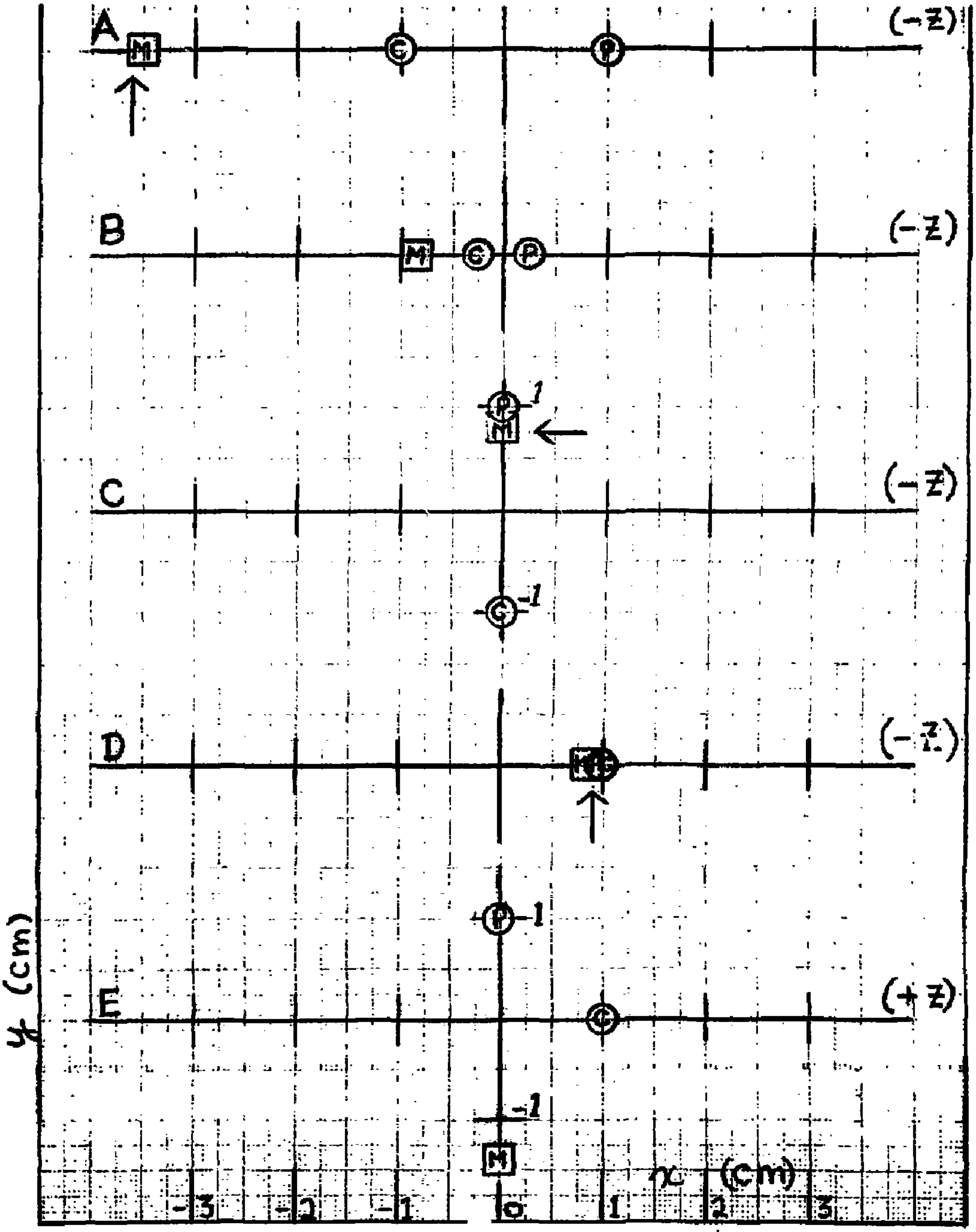


Fig. 11. Intersection of the drift surface of Fig. 9 with the solenoidal midplane.

Fig. 12. Graphic summary of results from the calculations of mapping along magnetic-field lines from the solenoidal midplane to the plugs, for various misalignment configurations. See Table 2 for the corresponding numerical summary. Symbols: P = position of displaced plug, C = position of displaced pair of transition Cees, M = position at plug midplane of magnetic-field line that is on axis at the solenoidal midplane (all three symbols plotted for the -z or +z end of the machine, as indicated). Arrow shows the position at the plug midplane of center of corresponding drift surface.



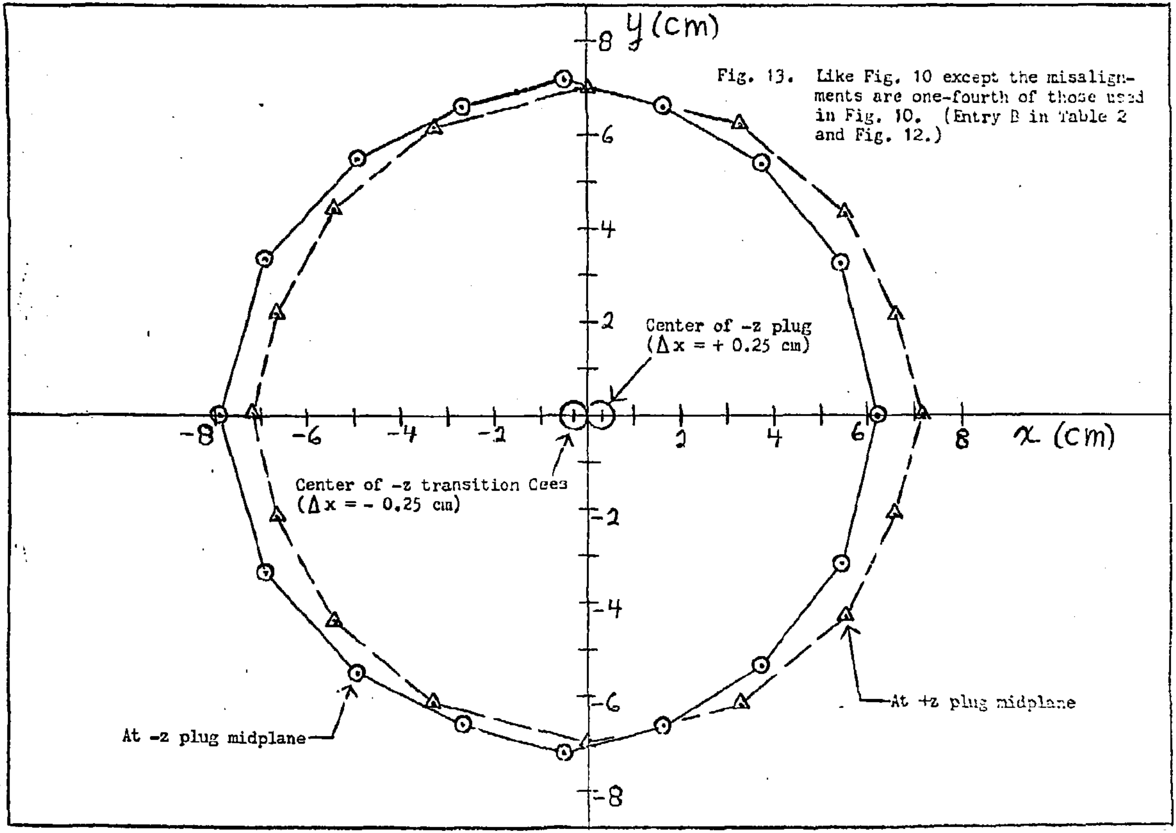


Fig. 13. Like Fig. 10 except the misalignments are one-fourth of those used in Fig. 10. (Entry B in Table 2 and Fig. 12.)

Fig. 14. Positions of transits through the solenoidal midplane for ion that becomes temporarily trapped in slight |E| dips away from the midplane region (320-eV D^+, 81° pitch angle). The general direction of precession is indicated.

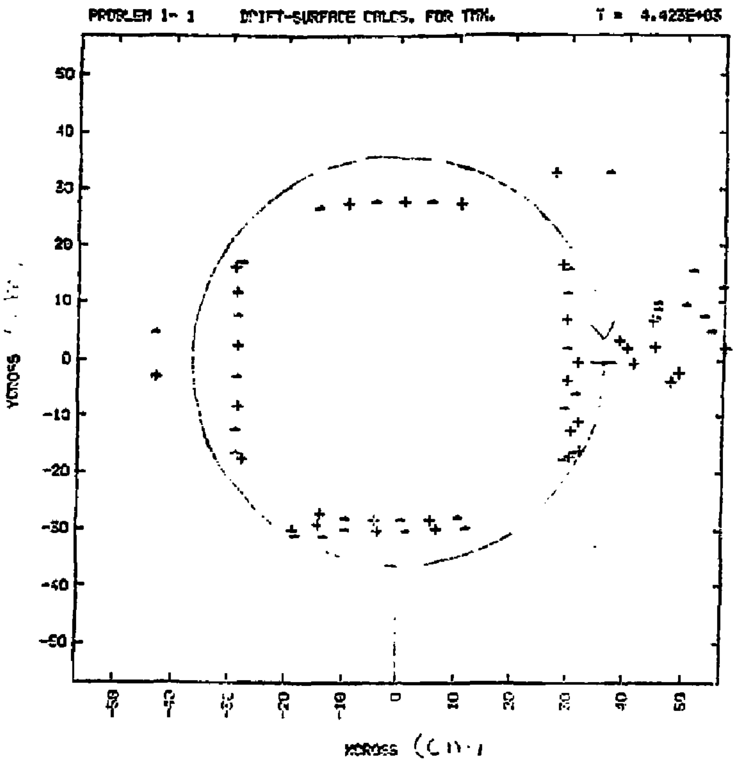


Fig. 15. Drift surface at solenoidal midplane after magnetic-field smoothing, for the same particle conditions as in Fig. 14.