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TMX UPGRADE MAGNET-SET-GEOMETRY DESIGN*

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Summary

A magnet set, consisting of 24 coils, has been designed for the TMX Upgrade (Fig. 1). Like the coil set designed for the TMX experiment, the coils for TMX Upgrade consist of a central-cell set with a minimum-B plug set on each end. Between the central cell and each end plug, there is a flux bundle recircularizing transition set.

Physics considerations (Table 1 and Ref. 1), require that the TMX Upgrade magnet set be almost twice as long as the TMX magnet set (14 m between the outer mirrors). The central circular coils are the only coils used from TMX.

The TMX transition set of two C-coils and an octupole are replaced by a C-coil and an Ioffe coil. The TMX plug composed of a baseball coil and two C-coils is replaced by an Ioffe coil, two C-coils and two circular coils.

A comparison between the TMX and TMX Upgrade magnet sets is shown in Table 2.

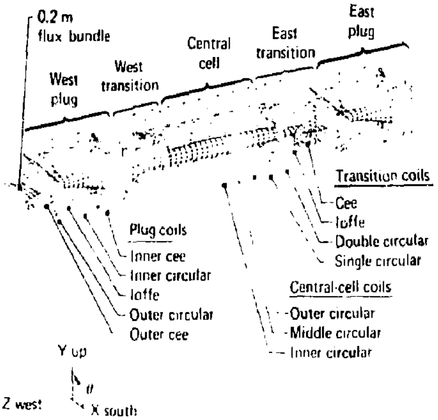

Fig. 1. TMX Upgrade magnet set.

Magnet Set Design History

In designing the upgrade magnet set, we initially kept the existing TMX baseball and C-coil plug set. In these designs we added an auxiliary sloshing cell (A-cell) outside of the TMX baseball plug. The first designs added a new mirror C-coil outside of the TMX magnet set (similar to MFTF-B). However, on the scale of the TMX, this configuration resulted in too narrow of a fan in relation to the ion gyroradius. Next, we thickened the fan by adding another C-coil at the inside of the A-cell next to the baseball plug. This design had open drift surfaces. We then tried a minimum-B field A-cell. This A-cell design was very similar to the final TMX Upgrade plug. The A-cell drift surfaces still remained open due to the interaction between the plug and the A-cell. To decrease this interaction, we separated the A-cell from the plug. The resulting on-axis B field then had four mirror peaks on each end. The separation created an additional well between the plug and the A-cell. The drift surfaces for this design were closed. However, the physics in the additional well between the plug and the A-cell was uncertain. Also, the magnet set had become too large, and consumed too much power. At that point, we decided to replace the existing TMX baseball plug and transition set with a new integral plug and sloshing cell.

Having decided to make an integral plug and sloshing cell, we no longer had the baseball plug to provide a MHD stable anchor for the magnet set. The

TABLE I. Magnet Design Considerations.

Engineering Considerations	Physics Considerations
● Neutral-beam access	● Magnetic-field profile and magnitude
● ECRH microwave access	● Ellipticity and thickness of the flux-bundle cross section
● Diagnostic access	● Radial well depth in the end cell (plug)
● Coil supports	● Closed particle drift surfaces in the end and central cells
● Power requirements	● Adiabaticity in the end cells
● Available space	● Radial transport in the central cell
	● MHD stability: flute interchange
	● MHD stability: ballooning interchange

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TABLE 2. Comparison of the TMX and TMX Upgrade Magnet Systems.

Parameter	Magnet system	
	TMX	TMX Upgrade
Vacuum-magnetic-field profile		
Central cell:		
Center field, T	0.2	0.3
Total length between inner mirrors, m	5.3	8.1
Axisymmetric mirror ratio	1:1	1.5:1
End cell (plug):		
Maximum field, T	2.0	2.0
Minimum field, T	1.0	0.5
Mirror ratio	2:1	4:1
Length, m	1.1	3.0
Radial well depth, %	4.0	0.5
Total length between outer mirrors, m	7.5	14.1
Particle and plasma confinement		
Typical end-cell adiabatic lifetime ($15\ keV\ H^+$, vacuum magnetic field) (s)	2.5	6.1
Particle-drift surfaces in the end-cell vacuum magnetic field	closed	closed
End-cell MHD beta limit	0.2	0.22
Central-cell MHD beta limit	0.07	0.16
Other		
Neutral-beam access	OK	OK
Closed mod B contours (for ECRH in Upgrade)	Yes	Yes

new integral plug had to provide this anchor. In addition to our final design, we also tried a yin-yang plug set. We rejected this design because the magnets were much larger, and they consumed twice as much power.

Magnet Set Design

General

The TMX Upgrade magnet set is shown in Fig. 1. The overall specifications are listed in Table 2. Figure 2 shows the magnet with all of the neutral beam access paths that must be provided, even though all of them will not be used at the same time. The sloshing and pumping beams are respectively at 45° and 18° to the coil-set axis. The center-cell beams are at 59° and 70° to the axis.

The magnetic field design is done with the EFFI[2] magnetic field code along with the preprocessing geometry code EIG.[3] Figure 3 shows the on-axis field strength. Figures 4 and 5 show the field profile for the east and west elevations. The profile shown is that of the design 0.15-m plasma-radius field line. The magnetic field design condition is that a 0.15-m radius flux surface at the plug minimum-B ($z = 5.68$ m) map to a circle at the center cell ($z = 0$ m). In addition, all of the physics requirements (Table 1) must be satisfied to a 0.2-m plasma radius; the 0.3-m field line must clear the machine. The rectangles plotted in Figs. 4 and 5 are cross sections through the coils (without cases as cut by the elevation plane.

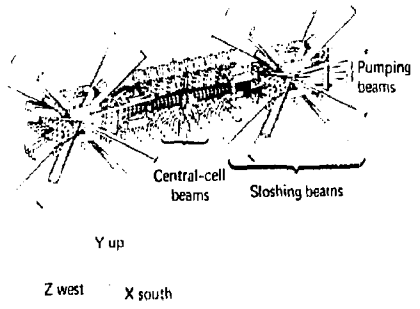

Fig. 2. TMX Upgrade magnet set with neutral beams.

Plug Design

Each end plug consists of five coils (Figs. 1 and 2). The plug set is symmetrical about its mid plane with each half rotated 90° with respect to the other. The two identical 59° C-coils provide 2.0-T mirror-field peaks, three meters apart. The three meter peak-to-peak distance allows the system to satisfy adiabaticity and beam access requirements. The C-coils are large to reduce field ripples within the plasma-flux bundle. The absence of ripples eliminates local negative curvature regions. The favorable (positive) curvature and geometric symmetry of the end plugs allows the design to meet the closed drift-surface, ballooning interchange stability, and flute interchange stability requirements.

The end-plug Ioffe coil, which spans the plug, shapes the minimum-B plasma into a circle near plug midplane. The outermost end of this coil is carefully shaped to allow access for the neutral beams (Fig. 2).

The two identical circular coils surrounding the Ioffe coil provide a gradual transition from the mirror field of 2.0 T to the minimum field of 0.5 T. This smooth, gradual transition of the field along the magnetic flux lines provides adiabatic confinement.

TABLE 3. Coil Set Specifications.

Coil	Major radius cm (a)	Minor radius cm (b)	Spacing cm (c)	Subtended ang' deg (d)	Bar length cm (e)	Axial location cm	Turns	Current Amp. (f)
End-Cell (Plug) Coils								
Outer C-coil	200	23	46	59		508(g)	22x12	4515
Outer circular	113					608	10x6	4494
Ioffe			110		210	558(h)	10x10	3049
Inner circular	113					508	10x8	4494
Inner C-coil	200	23	46	59		608(g)	22x12	4511
Transition Coils								
C-coil	72	23	46	180		303(g)	8x4	3437
Ioffe	45		90	180	106	274(h)	10x10	2455
Dbl Circular								
Outer	113					288	4x19	4406
Inner	113					279	4x19	4406
Sing. circular	113					270	4x19	1136
Central-Cell Coils								
Outer circular	113					156	4x19	3199
Middle circular	113					96	4x19	1971
Inner circular	113					36	4x19	2450

a = For C-coils, radius of large arc sections
b = For C-coils, radius of small arc sections
c = For C-coils, distance between center lines of large arc sections
For Ioffe coils, distance between center lines of adjacent bars.
d = Of large arc sections as seen from their center of curvature
e = Length of straight section
f = Total coil power is 24 MW
g = Axial location is center of curvature of major radius
h = Axial location is center of straight sections

The most important design conclusion is that there can be no negative curvature in the field lines throughout the plug. Negative curvature will result in either the drift surfaces being open or the plug being MHD unstable. If there is negative curvature but the plug is symmetric, the drift surfaces may still close; but the plug will be MHD unstable.

Careful design is required to eliminate all of the negative curvature throughout the plug. Generally, positive curvature is easier to obtain if the plug is shorter and the fan is thinner. However, the plug length is limited by access for the 18° pumping beams. The fan thickness is limited by the ion gyroradius. With these two limitations, the field lines through the plug are almost straight with very little curvature. This small positive curvature means the plug radial well depth is small (0.5%).

We had a particular problem with negative curvature near the mirrors in the narrow fan direction. If there is too much positive curvature in the wide fan direction, negative curvature begins to appear in the narrow fan direction. This situation is good for MHD stability but results in open drift surfaces. This negative curvature is barely perceptible, but it tends to occur at the transition end of the plug (due to the influence of

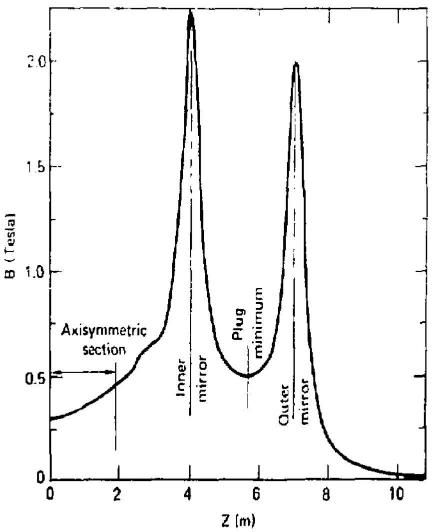

Fig. 3. On-axis field strength.

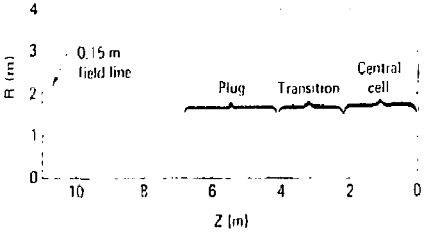

Fig. 4. Field-line profile, elevation, east end.

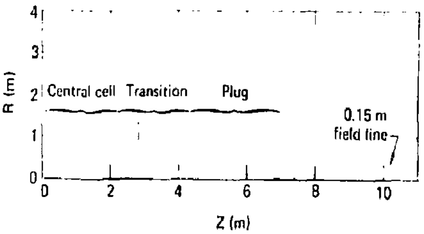

Fig. 5. Field-line profile, elevation, west end.

the transition coils) and not at the outer end. The result is a nonsymmetric plug, and the drift surfaces are open. The length of the Ioffe bar is important in eliminating this negative curvature. An Ioffe coil that is too short causes negative curvature near the plug center; one that is too long causes negative curvature near the plug mirrors in the narrow fan direction.

Negative curvature in the wide-fan direction is *eliminated by matching the plug C-coils to the Ioffe* coil. Also, a C-coil that is not high enough causes negative curvature due to the influence of the coil ends.

Figures 6 and 7 are elevation planes through the east and west plugs showing the plug detail. The coil cross sections are shown along with the mod-B contours and the 0.1-, 0.2-, and 0.3-m radius field lines. Note that the field lines are almost straight between the 1.0-T sloshing points. In order to pass the physics requirements (Table 1) along the 0.2-m field line, we *have to remove all negative curvature inside of the* 0.3-m field line.

Transition Design

The transitioning region between each end plug and the center cell is provided by a transition set consisting of a 180° C-coil and an Ioffe coil (Figs. 1 and 2). These two coils smoothly transform the plasma from a minimum-B elliptical shape to the circular central-cell plasma shape. This allows the central-cell region to *meet the stability, adiabaticity, drift surface,* and radial transport requirements.

The basic design philosophy is that as much as possible, the transition set should be similar to one-half of the plug set. The major difference is that the transition set should not produce the high mirror field. In fact, the transition set should contribute as little to the inner mirror field as possible so as not to affect the symmetry of the plug. In the upgrade design, both plug C-coils operate at the same current. The transition and central-cell coils cause the inner *mirror to be 12% higher than the outer mirror. Having* the transition set similar to one-half of the plug set allows the flux bundle to be circular inside of a 0.2-m plasma radius.

A dimensional limitation is that the transition set must fit inside the central-cell circular coils. This limitation on the major radius of the transition C-coil makes it difficult to completely remove a small field well between the plug and transition coils. This occurs along the widest transition region field line. To minimize this well (0.003 T), the transition C-coil *major radius is as large as possible and both of the* transition coils are as close as possible to the inner plug C-coil.

The returns on the inside end of the transition Ioffe are carefully designed to avoid another unwanted *mirror peak.* The currents in the adjacent arcs in this inner return flow in opposite directions. This causes the field due to this inside return to cancel on axis.

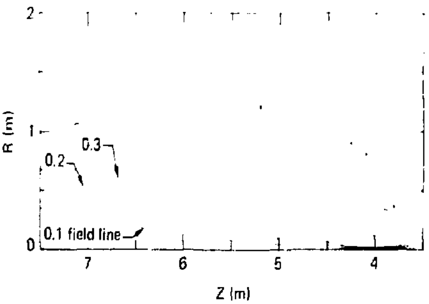

Fig. 6. Plug detail, elevation, east end.

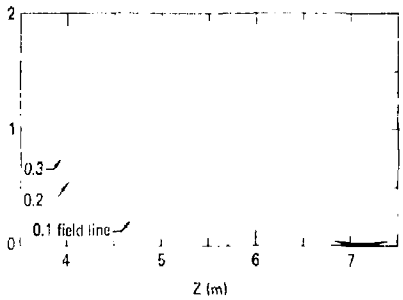

Fig. 7. Plug detail, elevation, west end.

The two transition coils affect the flux bundle differently in recircularizing. The narrow C-coil matches the inner plug C-coil. It affects the extreme transition field lines (0° and 90°) and has less of an effect on the intermediate 45° line. That is, it tends to produce a clover leaf flux bundle cross section at the center cell with the leaves pointed at 45°. The transition Ioffe matches the plug Ioffe. It affects the ± 45° *line and has less of an effect on the 0° and 90°* lines. In recircularizing this flux bundle, it tends to produce a clover-leaf flux-bundle cross section at the center cell with the leaves pointed at 0° and 90°.

The correct spacing between the Ioffe bars also eliminates this clover-leaf flux-bundle cross section. Too wide a spacing does not push the 45° line in enough. Too narrow a spacing pushes the 45° line in too much.

Additional axial field is required in the transition region to satisfy central-cell radial transport requirements and to create the axisymmetric central-cell mirror. *This field is supplied by a double and a single* circular coil (Figs. 1 and 2). These coils were fabricated previously for 2X experiment and were used on TMX. The double coil is two single coils enclosed in one vacuum case.

Central-Cell Design

The central-cell region consists of six circular coils. These coils are the same as the transition single coil, and are also from the 2X and TMX experiments.

Magnet Set

The TMX Upgrade magnet set is shown in Figs. 1 and 2. Table 3 lists the general specifications of the coil set.

REFERENCES

1. J. H. Foote, A. K. Chargin, R. H. Cohen, T. B. Kaiser, C. V. Karmendy, T. C. Simonen, and R. L. Wong, "TMX Upgrade Magnet System - Design Characteristics and Physics Considerations," Lawrence Livermore National Laboratory Report UCRL-86677 (1981).

2. S. J. Sackett, "EFFI-A Code for Calculating the Electromagnetic Field, Force, and Inductance in Coil Systems of Arbitrary Geometry," Lawrence Livermore National Laboratory Report UCRL-52402 (1978).

3. B. M. Johnston, EIG, Lawrence Livermore National Laboratory, to be published