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MAGNETIC DESIGN OF THE AXISYMMETRIC THROTTLE-COIL ADDITION TO THE TANDEM MIRROR EXPERIMENT-UPGRADE*

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Abstract

The TMX-U magnet set has incorporated new axisymmetric throttle coils and fan-reversing transition magnets. This new magnet geometry, which will allow for the experimental verification of new physics issues related to axicell tandem mirrors, encompasses both engineering and physics considerations. Engineering considerations include structural integrity plus neutral beam and diagnostic access. Physics issues include the stability and radial transport of the confined plasma. We have calculated the magnetic field using the magnetic field code, EFFI, and the plasma stability and surface curvatures using the plasma stability code, TEBASCO. Our magnet design allows the axisymmetric throttle mirror to be varied from the end-cell mirror value of 2 to a peak of 6 T.

Introduction

The Tandem Mirror Experiment-Upgrade (TMX-U) facility has been in operation for two years. Its magnet set [1] consists of 24 coils (Fig. 1). Specifically, the axisymmetric central-cell region has six circular coils. The ends of the plasma tube are plugged by two minimum-B end cells, which include two mirror C-shaped or C-coils, a quadrupole-producing Ioffe coil, and two circular coils. Between the central cell and each end cell, there is a quadrupole transition region with a C-coil, a Ioffe coil, and two circular coils; these act together to change the

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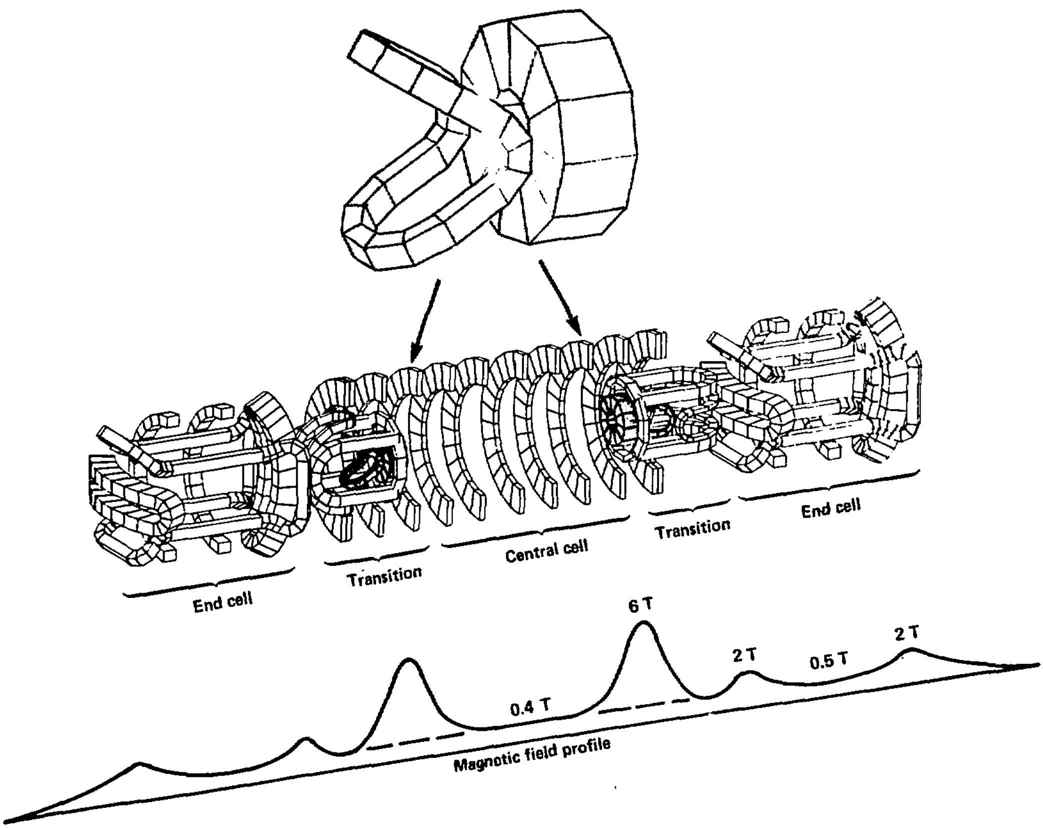

Fig. 1. Magnet array of TMX-U indicating the geometry and placement of the two new throttle coil inserts. Each insert consists of a reverse cee magnet and a throttle solenoid.

magnetic flux-bundle from the elliptical cross section in the end cell to the circular cross section in the central cell. Table 1 compares the magnetic field geometries of the original TMX [2], TMX-U [1], and the TMX-U throttle-coil modification (TMX-U Throttle).

Table 1. Comparison of the TMX, TMX-U, and TMX-U Throttle systems.

	Magnet system		
	TMX	TMX-U	TMX-U throttle
Central cell and transition:			
Center field (T)	0.2	0.3	0.4
Throttle field (T)	---	---	6.0
Axisymmetric mirror ratio	1:1	1.5:1	15:1
Total length between inner mirrors (m)	5.3	8.1	4.3
End cell (plug):			
Maximum field (T)	2.0	2.0	2.0
Minimum field (T)	1.0	0.5	0.5
Mirror ratio	2:1	4:1	4:1
Length (m)	1.1	3.0	3.0
Radial well depth (%)	*4.0*	*0.5*	0.5
Total length between outer mirrors (m)	7.5	14.1	14.1

Throttle-Coil Addition

The throttle-coil modification to the TMX-U magnet set consists of the addition of two coils to each of the two transition regions (Fig. 1). One of these two *coils is a high-field*, 6-T circular coil called the throttle coil. The other is a C-coil that produces a reverse-quadrupole transition field and thus creates a reversal in the transition-region flux-bundle fan; we call this a reverse C-coil. Table 2 lists the coil-set specifications.

The on-axis field strength is also shown in Fig. 1.

The existing mirror C-coils in each end cell produce four outer and inner mirror fields of 2 T at the ends. When each of the throttle-coil sets is included, they will produce two 6-T mirrors at the outside ends of the central-cell region (the inside ends of the transition region).

Figure 2 shows the magnetic flux-bundle. The "bow-tie-shaped" fans on both ends of this flux-tube are the minimum-B regions created by the end cells. The circular axisymmetric central-cell region is seen in the middle of the flux-tube. The outer end of this region is pinched by the new throttle coil. Just outside of the central cell is the reversal in the transition fan that is created by the added reverse C-coil.

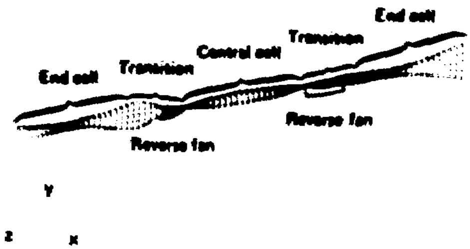

Fig. 2. Flux-bundle of TMX-U.

The addition of these two new coils permits:

- The study of the physics of axicell tandem-mirror machines, including radial transport, stability, plasma heating, and pumping power requirements.
- Improved central-cell plasma confinement [3,4]. Specifically,
  - The throttle coil reduces the number of particles that reach the bad-curvature transition region by a factor of 5;
  - The reverse C-coil reduces the averaged transition geodesic curvature by a factor of 2;
  - This combination reduces radial transport by a factor of 10.

Magnet-Set Design

Design Guidelines

The design guidelines were set by minimum performance requirements as well as cost and schedule. For cost and schedule reasons, we decided to change the existing TMX-U magnet set as little as necessary. In particular, the end cells were not to be altered or moved. We wanted the plasma size to remain at the existing 0.15-m end-cell radius with a plasma halo extending to a 0.25-m radius. Also, the new plasma configuration had to be magnetohydrodynamically (MHD) stable at the TMX-U design point (average end-cell beta of 0.165 and average central-cell beta of 0.125).

Initially we wanted to include a complete axicell with two high-field coils in the central axisymmetric region, similar to the tandem Mirror Fusion Test Facility (MFTF-B) geometry [4]. However, with the length restriction caused by fixing the end cells, we could not include a complete axicell without reducing the central cell to essentially zero length. When we attempted to gain some length by shortening the transition region, the increased normal curvatures (curvature normal to the surface) made the *configuration MHD unstable*.

Because the physics of the axicell can be studied in a geometry having a single throttle coil, we chose to modify the TMX-U magnet geometry by adding one throttle coil and one reverse C-coil in each transition region. All of the transitioning was thus done within the existing transition length.

Table 2. Coil-set specifications.

	Major radius (cm)[a]	Minor radius (cm)[b]	Spacing (cm)[c]	Subtended angle (deg)[d]	Bar length (cm)[e]	Axial location (cm)[f]	No. of turns	Current (A)[g]
End-cell (plug) coils								
Outer C-coil	200	23	46	59		508[h]	22 x 12	4515
Outer circular	113					608	10 x 8	4668
Ioffe			110		210	558[i]	10 x 10	3075
Inner circular	113					508	10 x 8	4668
Inner C-coil	200	23	46	59		608[h]	22 x 12	4511
Transition coils								
C-coil	72	23	46	180		303[h]	8 x 4	4930
Ioffe	45		90	180	106	274[i]	10 x 10	4838
Reverse C-coil	15	24	48	120	25	254[h]	8 x 6	3613
Throttle	29					213	24 x 20	5965
Dbl. circular								
Outer	113					288	4 x 19	0
Inner	113					279	4 x 19	0
Sing. circular	113					220	4 x 19	1136
Central-cell coils								
Outer circular	113					156	4 x 19	3199
Middle circular	113					96	4 x 19	2800
Inner circular	113					36	4 x 19	2457

[a] C-coils with radius of large arc sections.
[b] C-coils with radius of small arc sections.
[c] C-coils with distance between center lines of large arc sections; Ioffe coils with 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] Distance from center of central cell.
[g] Total coil power is 37 MW.
[h] Axial location is center of curvature of major radius.
[i] Axial location is center of straight sections.

Design Details

Our design calculations used the EFFI [5,6] magnetic field code together with the TEBASCO [7] plasma stability code. Our magnet design objective is the same as that for the MFTF-B transition magnet set [8]. Simply, the objective is to minimize the integral of the geodesic curvature (curvature in the surface) over the length of the transition region. This minimizes the central-cell radial transport and also reduces the plasma distortion due to parallel currents in the plasma. However, MHD stability is controlled by the normal curvature (curvature normal to the surface). As positive normal curvature is stabilizing and negative normal curvature is destabilizing, the transition geodesic curvature integral must be minimized without an excessive increase in the negative normal curvature.

Ideally, the transition design should make the geodesic curvature integral zero throughout the transition region. However, with the allowable transition length, the geodesic curvature integral cannot be made zero without introducing too much negative normal curvature and making the geometry MHD unstable.

Typically, the geodesic curvature integral is minimized by a "bow-tie" flux-bundle shape similar to that found in the end cell. This symmetry causes the positive and negative geodesic curvature contributions to cancel, thus minimizing the curvature integral. This flux-bundle shape, generated by opposing quadrupole fields, was introduced into the existing transition fan to create a reverse fan.

Figure 2 shows the reverse transition fan that the added reverse C-coil generates. Figures 3a-b and 4a-b are EFFI outputs depicting elevation cross sections cut through the flux-bundle and the coils.

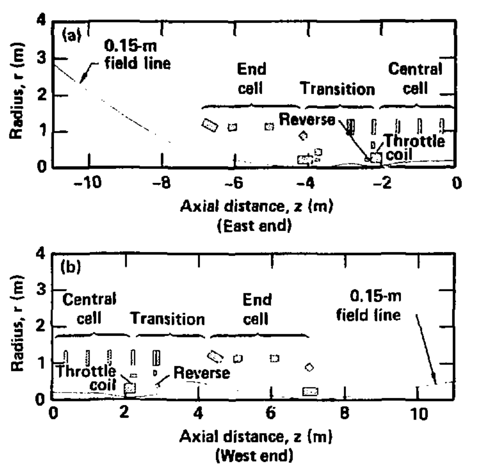

Fig. 3. Field line profile and elevation view of the magnets for the (a) east end and (b) west end.

In particular, Fig. 3a-b shows the east (-z) and west (+z) halves of this elevation view; Fig. 4a-b illustrates the transition elevation view in more detail. Note that the rectangles are cross sections of the magnet conductor bundles, and the flux bundle is the 0.15-m flux line. The reverse transition fan can be seen in both Figs. 3a and 4a.

Figure 5 is a TEBASCO output showing the normal (Yah) and geodesic curvature (Yuh) plots through the machine. Note in particular the geodesic curvature in

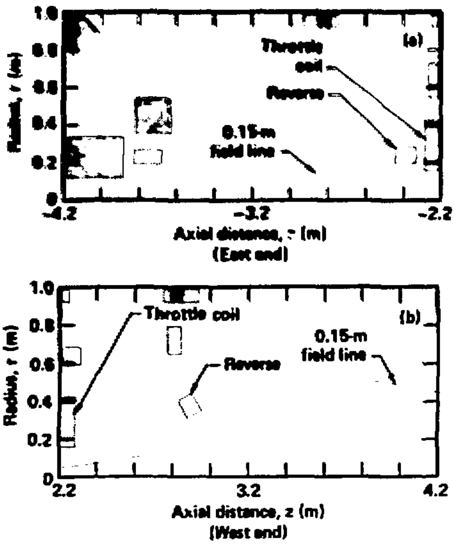

Fig. 4. Detail and elevation view of the transition-region magnets for the (a) east end and (b) west end. Note the reverse fan.

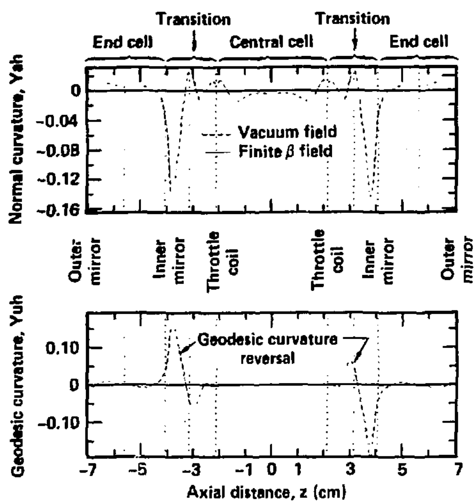

Fig. 5. The geodesic and normal curvatures for the TMX-U Throttle.

the transition region. The large dip is created by existing TMX-U fan as it transitions from the end cell to the central cell. The smaller cancelling peak is generated by the added reverse C-coil. This transition design creates as large a reverse peak as possible within the transition length allowed.

To allow the full range of physics, the plasma-to-magnet clearances are determined with the throttle-coil mirror field lowered to the 2-T value at the inner end-cell mirror. At this field the 0.23-m-radius end-cell field line clears all of the machine magnet cases.

Because of the additional flux-bundle twisting required to minimize the geodesic curvature integral, the geometry with the added throttle magnet and reverse C-coil is slightly less MHD stable than the original TMX-U geometry. However, as seen from the TEBASCO stability plot in Fig. 6, the TMX-U design point is still within the stability limit.

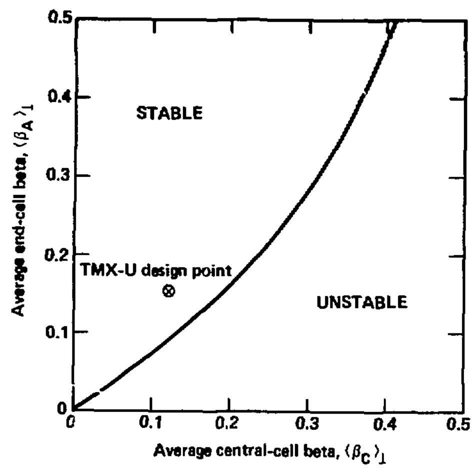

Fig. 6. Magnetohydrodynamic (MHD) rigid-ballooning-mode stability limit for TMX-U Throttle.

Conclusion

The new throttle coil and reverse C-coil will be included in the TMX-U magnet set when the physics experiments using the existing magnet set are completed. The design and fabrication of both coil sets are essentially finished. Reference [9] describes the fabrication of the coils and related mechanical issues.

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