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Introduction

The magnetic field design and the mechanical design of the TMX magnet system were previously reported by Chen[1] and Hinkle[2]. This paper is a summary of the work that has been accomplished in the two years since then.

Magnet System Description

The TMX coil set configuration is shown in the computer generated drawing in Fig. 1. For a clearer view of the octupole and the other transition-coils, a 90° section has been removed from the solenoids. The magnet set is composed of east and west plug-sets, east and west transition sets, and the center-cell solenoid coils. The plug-sets each have a baseball-coil with inner and outer C-coils nested within the baseball lobes. Each transition set consists of an 86°-C-coil, a 180°-C-coil and an octupole. The center-cell set has six solenoid coils. The west half of the magnet set is the reflection of the east half, rotated 90°. The TMX magnet set is half symmetric about it's axis.

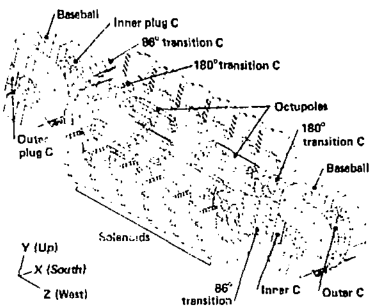

Figure 1. Computer generated drawing of the TMX magnets (with a 90° section of the solenoid coils removed)

Magnetic Field Design Points

The two TMX design points are shown in Table 1.

Table 1. TMX Design Points

Plug Plasma radius	7 cm	15 cm
Plug Center Field	10 kG	10 kG
Plug Axial Mirror Ratio	2	2
Center Cell Field	0.5 kG	2 kG

For all operating conditions, the circular flux-bundle containing the plasma at the plug-center maps into a circle at the center-cell.

The magnetic-field calculations were made using the MAFCO3 and EFFI[4] computer codes. For the 7 cm, 0.5 kG design point, Figures 2a and 2b show an elevation view ($\phi = 90°$) of the magnet set with the 7 cm, 90° field line. This elevation view is in the vertical plane that contains magnet set axis (z-axis). The coils are shown in cross-section as intersected by this plane. Fig. 3 shows the on-axis magnetic-field strength.

Table 2 and 3 list the electrical current, coil voltage, and coil power for the individual coils at the two design points.

Fig. 2a

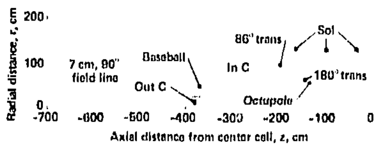

Fig. 2b

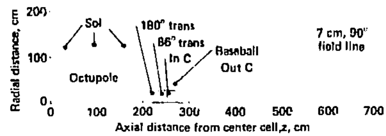

Figure 2a & 2b. Cross section through the machine showing the 7cm flux line on the east side (Fig. 2a) & West side (Fig. 2b)

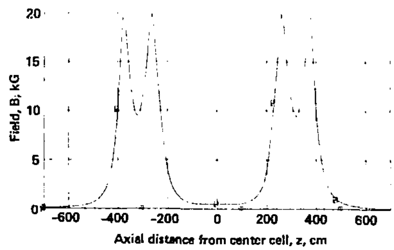

Figure 3. Field strength as a function of length for the 7cm, case

Table 2. TMX 7 cm, 0.5 kG Design Point Magnet Current and Power*

Coil	Current Amp-Turn	Current A	Coil Voltage** V	Coil Power ** kW
Baseball	1.478×10^6	4561	912	4161
Outside Plug C-Coil	4.570×10^5	4570	246	1127
Inside Plug C-Coil	3.851×10^5	3851	208	800
86° Transition C-Coil	1.387×10^5	2889	66	192
180° Transition C-Coil	1.185×10^5	1851	59	109
Octupole	8.302×10^3	691	8	5
Outer Solenoid	-6.000×10^4	-289	-25	19
Middle Solenoid	-5.001×10^2	-6	-0	1
Inner Solenoid	3.276×10^4	431	13	5
MACHINE TOTAL ***				12.85×10^3***

* The values are per coil. The values for the east and west halves of the machine are equal.
** Does not include leads.
*** Both halves of the machine. (Each half consumes 6.43×10^3 kW.)

Table 3. TMX 15 cm, 2.0 kG Design Point Magnet Current and Power*

Coil	Current Amp-Turn	Current A	Coil Voltage** A	Coil Power ** kW
Baseball	1.392×10^6	4296	859	3691
Outside Plug C-Coil	4.960×10^5	4960	267	1328
Inside Plug C-Coil	4.401×10^5	4401	237	1045
86° Transition C-Coil	2.613×10^5	5443	125	681
180° Transition C-Coil	2.662×10^5	4159	133	553
Octupole	4.002×10^4	3335	38	122
Outer Solenoid	4.000×10^4	526	16	8
Middle Solenoid	8.200×10^4	1078	34	37
Inner Solenoid	1.030×10^5	1355	43	58
MACHINE TOTAL***				15.07×10^3***

* The values are per coil. The values for the east and west halves of the machine are equal.
** Does not include leads.
*** Both halves of the machine. (Each half consumes 7.53×10^3 kW.)

General Construction Features

The general construction features of the TMX are covered in Ref. 2. It should be noted that the 210°-coil geometry shown there was changed to a 180° geometry. A typical octupole-coil during fabrication is shown in Fig. 4.

The construction of the magnets posed few problems. Those problems that arose were insignificant, usually related to poor fit-up of the potting cases or vacuum cases. The potting cases are all two-piece designs. The conductor of each coil was wound on the inner case. Later, the outer-case was slipped over the finished winding. It was intended that seams between the two cases be sealed with duct-tape and epoxy prior to the vacuum impregnation of the coil. The first two coils which were fabricated, were sealed in this manner but it

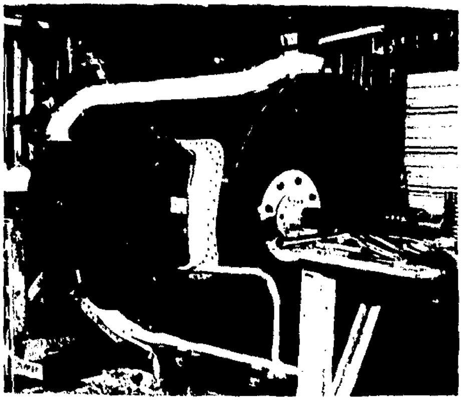

Figure 4 Octupole coil during fabrication

took far too long to get the potting-case seams free of leaks. Therefore, on all subsequent coils the potting cases were welded together.

This approach was not without its problems. Although care was taken to keep the heat generated during welding low, two magnets showed low resistance through the insulation from the conductor to the case after the potting cases were welded. The location of each short was found by using a double wheatstone bridge. The shorts were cleared by first removing the potting cases in the area of the short and then digging out the poor insulation. The insulation was then replaced, followed by a new section of case.

Coil-case to conductor shorts within a magnet also occured at four different times while the vacuum cases were being welded on. In each case they were cleared by using the same repair procedure.

None of these shorts have reoccured.

Coil Cooling

The TMX coils are all water cooled. The cooling water paths are long, and thermal equilibrium in the water and the copper can be assumed. An analysis of the 180°-transition coil shows that thermal equilibrium is reached by about 85% of the coil.

Also, comparisons with measured water temperatures show that the coil cooldown after the electric pulse can be modeled as a lumped thermal-capacitance system with an instantaneous heat release into the copper at the end of the current pulse. This lumped copper-capacitance then gives up its heat to the lumped water-capacitance and raises its temperature to that of the copper.

This model gives the coil temperature decay as:

$$\frac{\Delta T}{\Delta T_0} = e^{-t/\tau}$$

Here, ΔT is the temperature rise from ambient, ΔT_0 ia the instantaneous initial temperature rise in the copper, t is the time since the end of the current pulse, and τ is the system time constant given by:

$$\tau = \frac{(WC_p)_{Cu}}{(WC_p)_{H_2O}}$$

Here, $(WC_p)_{Cu}$ is the total copper heat capacity, and $(WC_p)_{H_2O}$ is the total flowing water heat capacity rate. Table 4 lists the time constants and the initial temperature rise for several coils.

Table 4.

Cooling Time Constants and Initial Temperature Rises

Coil	Initial Temp. Rise, T_0 °C	Time Constant τ, sec
Baseball	9	127
Plug C-Coils	19	25
86° Transition	20	19
180° Transition	14	36

TMX Magnet System Structural Analysis

Three types of forces act on the magnet-system structural-members; dead weight, magnetic forces, and earthquake loads. The magnet structural elements are designed to resist these loads.

The magnetic forces are the largest of the three. These forces act on the quadrupole coils by trying to open them up into a ring. The magnitude and direction of the forces were predicted for each of the coils using the EFFI[4] computer code.

The coil restraints which resist these forces were analyzed using simple analytical models. In addition, a finite-element analysis of the plug set structure made using the SAP4[5] code. The code predicts that the maximum stress in the restraint structure which is fabricated from 21% Cr - 6% Ni - 9% Mn stainless steel is less than 14.5 ksi. In addition, it is expected that even with a stress concentration of 5 near the corners, neither the yield stress, 68 ksi, nor the endurance limit, 49 ksi, will be exceeded. The code model also predicts that the largest displacement will occur on the jaws of the plug-C-coil. It was predicted to be about 0.16 in.

The magnet system is expected to be cycled to full power for less than 100,000 shots. With the exception of the 21-6-9 stainless plug-structure already discussed, the rest of the magnet case and restraint material has an endurance limit larger than the yield strength. Fatique is not expected to be a problem because most of the coil-case and structure areas are smooth sections without stress concentrations. In the filet welds that have a stress concentration, the stress intensity is less than the endurance limit for the material at 100,000 cycles.

The octupole magnet restraint structures were proof-tested by running the magnet to full power for 300ts before they were installed.

The deflection predictions of the plug set were tested by using linear deflectometers in the jaws of the baseball coil, for each plug, east and west. The power was limited to 25% for the first few shots, then increased to 50%, 75% and 100% of full power. During the test, the deflectometer was shown to be insensitive to the magnetic fields. The results of the tests corroborate the code prediction. The maximum detected deflection is the Baseball magnet jaws was .025 in. The maximum deflection that the code predicted was .040 in. The maximum observed deflection (observed visually) was about .15 in. This occurred in the lobes of the plug C-coils as predicted by the code.

The large axial magnetic forces on the plug and transition sets were predicted by using the computer code EFFI. Within each coil set, these forces are transferred from an individual coil to each coil restraint through the filet welds which join the coils together. The welds are made with AISI type 308L weld material and are designed to resist the combined axial and tensile loading without exceeding 38% of the parent metal yield strength.

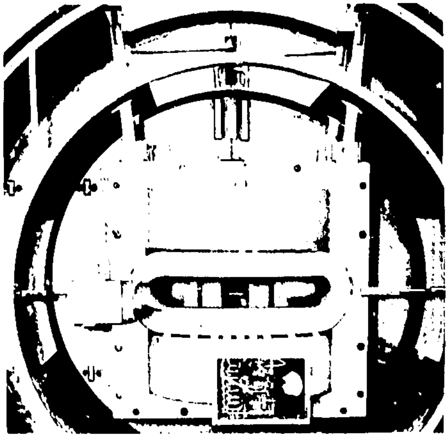

Figure 5 East plug set (with lead-box cover off)

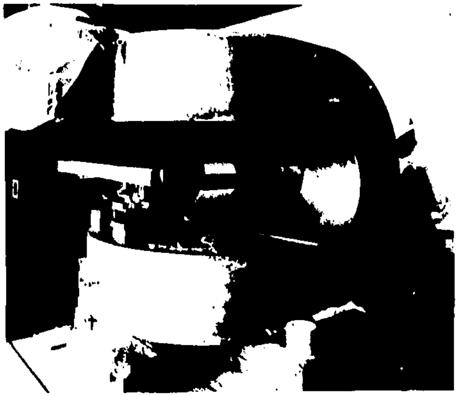

Figure 6 Baseball coil with magnetic alignment devicewithin the jaws

The axial forces are transmitted through the coil structure into 2" o.d. stainless steel rods. From there they are transferred into the center-cell vacuum-vessel. The stainless-steel compression-rods were designed as columns using the Johnson Parabola Formula[7]. All rods have a margin-of-safety of 4 or greater.

Each of the magnet sets are suspended from the vacuum chamber by stainless-steel hangers which allow some adjustment in all six degrees-of-freedom. The exceptions to this are the octupoles and solenoid coils which rest on adjustable footings. The hangers support the dead load while not exceeding 60% of the yield strength of the material. The magnets are prevented from swaying during an earthquake by sway bars which can restrain a 1/2 g static load without damage. The hangers and sway bars are shown in Fig. 5.

Alignment of the Magnets

During the construction of the magnets much work was done to align the system correctly. The work consisted of five tasks. First, the type and amount of tolerable misalignment were determined. Second, a method of establishing the magnetic center line of each coil and each group of coils was invented. Third, care was taken to align each coil in the plug and transition sets while the sets were being welded together. Fourth, the magnet groups - the plug sets, the transition sets, the octupoles, and the center cell solenoids - were aligned in the machine before the magnet system was operated. Finally, the magnets were tested to judge the success of the alignment.

For the plug and transition sets, two alignment criteria were established. One is that the magnetic center lines of all magnets of each set must be concentric with the machine axis within 4.5 mm. This criterion, in addition to limiting the magnetic center-line radial variation to something less than 4.5 mm, in effect reduced the tolerable angular variation about the x and y-axes to less than 1.5°. The second requirement is that angular misalignment of each magnet of these sets about the z-axis must be less than 1.5°. The radial-variation criteria is based on recommendations made by Foote.[8]

The angular misalignment criteria, unfortunately, are not yet based on analytical work but rather were the best values obtainable from the alignment method used. Work is now in progress to determine the analytical bases for the angular misalignment.

The alignment criteria for the octupole coils are the same as those for the plug and transition sets except that the center-lines used are not the magnetic center-lines but rather the geometric center-lines. This compromise was made because the method of determining the magnetic center-lines of the other coils could not be adapted to the octupoles.

Although these criteria were judged to be adequate, analytical work to substantiate this is in progress.

No formal alignment criteria were established for the center-cell solenoids, because the resulting field lines are somewhat insensitive to each solenoid's position. The alignment method used put them concentric with the machine axis within 3 cm and limited the rotations about the x and y-axes to less the 1°.

Three methods of sensing each coil's magnetic axis were considered. The use of a gaussmeter was considered but rejected because plotting the magnetic field by hand would take too long and, more importantly, because we doubted that the proposed technique was accurate enough. For a short time, we considered a kind of electron gun, one which we could use to watch the charged particles follow the field lines. This method was rejected, because the apparatus could not be fabricated in time. We chose the scheme of exciting each coil with an alternating current while sensing the minimum field region with sensing coils. The apparatus used in this method is shown located in the jaws of a baseball coils in Fig. 6. This technique was used on all of the quadrupole coils but not on the octopoles or solenoid coils.

The apparatus, designed to find the magnetic center-lines, consists of a number of sensing coils which were carefully positioned in a cruciform frame so that the sense-coils winding axis can be adjusted perpendicular to the magnet field-line - showing the

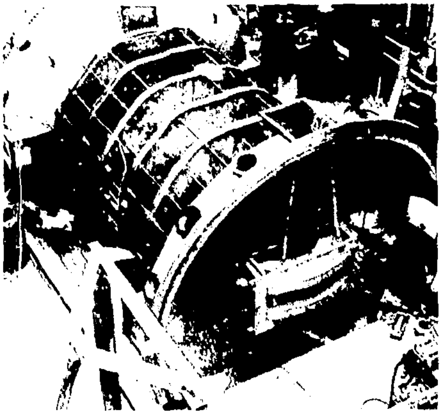

Figure 7. East end view. Tandem Mirror Experiment during construction. (Note the East Transition set on the hangers)

position of minimum excitation. The frame was held by a clamp which allowed the beam to be rotated about its axis. The clamp was placed on a wood stand which allowed good control over the horizontal and vertical movement.

In operation, the magnetic axis is found using at least four coils - two each, perpendicular to each other, on each end of the longest beam. In addition, the proper angular position about the beam axis is sensed by two coils on the cross-beam. The sense-coil output is about 55 mV in a perpendicular 0.1 gauss field. Each magnetic center-line was found by moving each end of the beam horizontally and vertically as well as by rotating the cross-piece until all sensing coils showed a minimum excitation. Each magnet was then permanently marked so that crosshairs could be mounted for the visual alignment to come later. This technique was precise, easily repeating the center line position to within 1 mm. It could also repeat rotation to less than 0.25°.

Once the coil cases were permanently marked, brackets were added to hold the removable crosshairs. The crosshairs on the octupole magnets show the geometric rather then magnetic centerline. With the crosshairs in place, an optical alignment telescope was used to view the potential misalignments. The plug sets and transition sets are welded groups of coils with no option of adjustment once welding was complete. Therefore, the alignment was carefully controlled while the sets were being welded so that the coils were placed on a common center. The accepted misalignment was 1.5 mm at each end, with axial rotation limited to less than .25°.

Early in the machine assembly cycle a common machine center-line was established. As magnets and magnet groups were installed their alignment was managed by viewing each set of crosshairs with the optical alignment telescope adjusted to the machine axis. The alignment soon became routine, since each set of coils permits adjustment for all six degrees of freedom.

After all of the magnets were installed, the alignment of each set was checked and adjusted so that it was concentric with the axis formed by the plug-set crosshairs. Then each coils position was checked while the vacuum vessel was cycled to vacuum and back. No movement was detected. Alignment was also checked after powering the magnets a few times. No change in alignment was detected. A typical coil set is shown installed in the east chamber in Fig. 7.

It is difficult to check the alignment of the system during the operating life of the experiment, because certain hardware which obstructs the line-of-sight down the machine axis must be removed.

Our operating experience with the aligned system indicates that while the system as a whole works as designed, some experimental diagnostic devices are particularly sensitive to proper coil alignment. In fact, the startup-streaming guns and the Light Ion Beam Probe were used recently to correctly predict an unexpected rotation of the West plug set. This test was useful as it was done with the machine at vacuum. It was corroborated when the machine was let up to air.

The Light Ion Beam Probe seems to be very sensitive to the coil alignment. This is the subject of on going work and may cause new, more strigent coil alignment criteria.

Future TMX, Thermal Barrier

Magnetic design studies are currently being made to modify the existing TMX coil set and to create a "thermal barrier[9]" in the magnetic field. This concept improves the reactor power gain (high Q) by thermally isolating the center-cell electrons from those in the plugs. From a magnetic field design viewpoint, the concept involves adding additional magnetic wells to the existing field.

Due to these space limitations inside of the TMX coil set, we are currently considering adding thermal barrier coils outside of the existing set.

Acknowledgments

The construction of the TMX magnet system in the allotted time was possible only because of great personal sacrifices of many people. We wish to express our gratitude and appreciation to the TMX coordinators, operators, technicians, and coil shop personnel and to the LLL coordinators, machinists and welders, all of whom provided timely, critical support.

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