Fermi National Accelerator Laboratory

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Mechanical Support of Superconducting Coils *

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Cold iron magnets use the iron yoke and skin for mechanical support of the collared coil assembly. A variety of designs, including horizontally and vertically split yokes, "collarless" magnets and conductor block geometries, have been considered for use with collared coils. This note qualitatively compares the support mechanisms by estimating the amount of coil "overcompression" necessary for the magnet to achieve the same mechanical condition in the cold, powered state. These designs inspect magnet limitations by suggesting means to reduce the peak coil compressive load, allowing higher central magnetic fields to be reached.

Introduction

In a mechanical sense, cold iron dipole magnet systems typically consist of four major components; the coil, collar, yoke and skin. The coil is the component to be restrained. The electromagnetic loads distributed in the coil during operation not only must be contained, but prepared for by the proper compression of the coil in its cold unpowered state. Although feasible in lower field magnets such as used in the Tevatron, cost constraints and higher fields have made the use of collar only support structures inviable.

At present, several collar/yoke/skin arrangements have been tested, to varying degrees of success. SSC magnets using horizontally split yokes with various collar yoke interferences have been tested. Recently a vertically split yoke was also tested on an SSC short magnet. CERN has recently tested short (one meter) magnets which have aluminum collars, vertically split yokes, and either aluminum or stainless steel skins successfully. The Texas Accelerator Center (TAC) has designed a "superferric" dipole which incorporates a new conductor geometry and support scheme. Other designs, including a "collarless" magnet, have been proposed. Here we try to qualitatively weigh the merits of each design.

Designs considered include:

I. Horizontally Split Yoke

- A.) Vertically Unsupported
- B.) Vertically Supported - Collar Keys Tight
- C.) Vertically Supported - Collar Keys Loose

II. Vertically Split Yoke

- A.) Vertically Unsupported
- B.) Vertically Supported - Collar Keys Tight
- C.) Vertically Supported - Collar Keys Loose

III. "Collarless" Style Magnet

IV. TAC Style Support Structure

Horizontally Split Yoke

The horizontally split yoke is the design which has traditionally been used on the SSC magnets. It is shown in Figure 1.

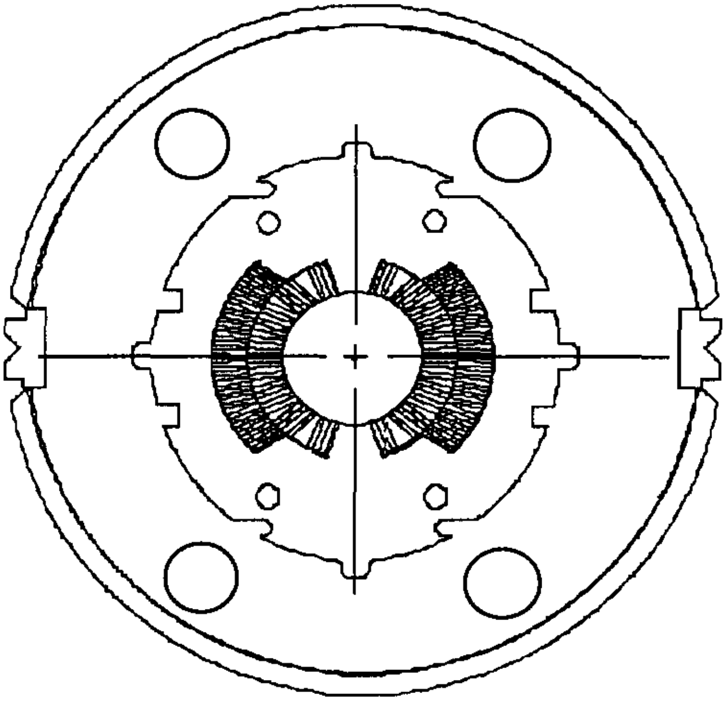


Figure 1. Horizontally Split Yoke

The horizontally split yoke magnet can be made with the collared coil vertically unsupported, vertically supported with the collaring keys tight or vertically supported with the keys loose, depending on how the collar is designed. If the collar is unsupported all the preload is contained by the collars. If the collar is supported but the keys are tight, the preload is shared by the collars and the skin. If the collar is supported with the keys loose, the skin and iron are containing all the preload. The collars are acting only as spacers. If the collars are vertically supported, a parting plane gap might open in the iron when the magnet is warm.

A problem with the horizontally split yoke is the maintenance of the collar-yoke interference at the midplane after cooldown. The collar material (traditionally stainless steel or aluminum) shrinks more when cooled than the iron. Maintaining the interference fit between the collars and the yoke when cold therefore requires a very large interference when warm. If an adequate interference is not achieved, the collar becomes unsupported horizontally when cooled. It then must resist the Lorentz loads alone until it deflects enough to close the collar-yoke gap. This results in unwanted coil motion. One possible solution to this problem is the use of a collar material which has a lower coefficient of thermal expansion than the iron, e.g., Kawasaki stainless steel.

Each of the horizontally split configurations has a different preload scenario. They all have the same assembly procedure.

Assembly Procedure for Horizontally Split Yoke

1.) Press collared coil vertically in collaring press just enough so collaring keys can engage.
2.) Hydraulically drive in collaring keys till collared coil is closed.
3.) Press sufficiently in yoke and skinning press to gain intimate contact between the iron and skin.
4.) Weld the skin shut. The skin becomes prestressed when welded and clamps tightly around the iron. When the press pressure is removed, a parting plane gap might open in the iron.

Vertically Split Yoke

The vertically split yoke is shown in Figure 2.

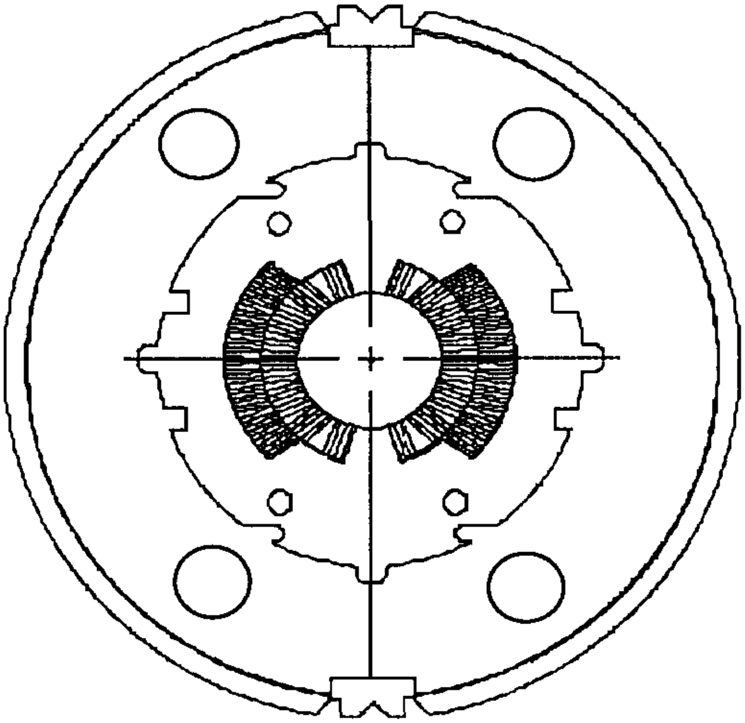


Figure 2. Vertically Split Yoke

The vertically split yoke can also be used with the collared coil vertically unsupported, vertically supported with the collaring keys tight, or vertically supported with the keys loose. Since the split in the iron is on the vertical axis no parting plane gap can appear. The iron lamination takes the preload while the skin takes the Lorentz forces when the magnet is powered. Each of the vertically split configurations has a different preload scenario. The assembly procedure is the same as that for the horizontally split yoke.

A gap could be left between the vertically split iron laminations when the magnet is warm. The gap would close when the magnet is cooled if the skin shrinks faster than the other magnet components, including the coil. The vertically split yoke has typically been considered for use with a stainless steel skin. An aluminum skin could be substituted for the stainless steel. The aluminum skin, having a higher coefficient of thermal expansion than stainless, will close the gap, causing preload to increase when the magnet is cooled. This is not certain to occur if stainless steel is used. Analysis could be done to determine whether a stainless steel skin could close this gap. In any case a greater preload increase could be achieved during cooldown by using an aluminum skin.

The "Collarless" Magnet

The collarless magnet is shown in Figure 3.

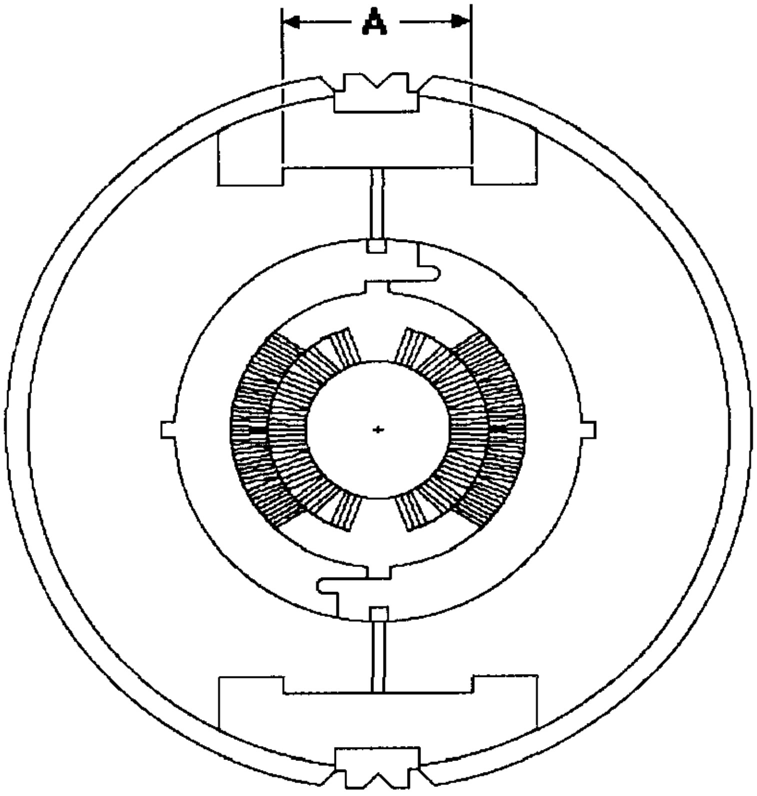


Figure 3. (shown in warm free state)

This configuration is very different from either the conventional horizontally or vertically split yokes. It is called "collarless" because the collar is very weak and does not, in theory, carry any of the coil preload. It is made of two pieces, a "pole insert" and a vertically split lamination which surrounds the coil. The collar functions merely as a spacer between the coil and yoke. The iron is split vertically as is the skin. An aluminum bar is used to hold the iron together. The preload is taken by the iron, aluminum bar and the skin.

Assembly Procedure for the Collarless Magnet

1.) Vertically split collars are placed onto coils, closed and keyed. Very little preload is used to close the collars. They are designed so that their outside vertical diameter is the same size as the iron inside vertical diameter. Their outside horizontal diameter is larger in the undeflected state than the iron inside horizontal diameter. This will allow the coil to be expanded horizontally, keeping the preload very low in the free state.

2.) The collared coil assembly is placed into the vertically split iron and closed until the aluminum bars can be inserted. The press pressure can then be removed and the aluminum bar will hold the assembly together in the free state.

When the "iron assembly" (the iron and aluminum bar without the skin) is in the free state, the keys which hold the collars together will be loose. All the preload will be taken by the aluminum bar and the iron laminations. The aluminum bar will be in tension. There is a vertical gap in the iron which can be closed when the magnet is cooled.

3.) The iron assembly is placed in a vertically split skin and pressed sufficiently to gain intimate contact between the iron and skin.

4.) The skin is welded shut. After welding the skin, the aluminum bar is still in tension, but less tension than before the skin was welded. The preload is being split between the aluminum bar and the stainless skin. The skin internal stresses will include welding stresses plus some portion of the preload.

The aluminum bar must be made thick enough to take the coil preload without yielding. Dimension "A" (see Figure 3) can be adjusted to make the vertical gap in the iron close by an appropriate amount during cooldown. Ideally, one would like the aluminum to shrink as much or more than the coil. This would keep the coil from losing preload when the magnet is cooled. To do this, though, might cause the iron to close faster than the skin is shrinking, making the skin loose on the iron (and forcing the aluminum bar to take all the preload, no longer sharing it with the skin). Dimension A must therefore be sized so that the gap in the iron closes as much as is possible without the skin coming loose. The relative contribution of the aluminum to the preload would be increasing as the skin would be decreasing. The contribution of the skin should never fall to zero, or the skin would be loose. It has yet to be determined whether this fine balance of shrinkages between components can be achieved given the variances in coil sizes and tolerances of component parts.

Since the collar is used only as a spacer in this design, it is desirable that the collar material have the lowest possible coefficient of thermal expansion. A material which shrinks less than the iron when cooled could solve the problem of the skin coming loose mentioned above. The aluminum bar could be made to shrink at a rate which causes the preload to increase without the skin coming loose.

The collarless magnet could also be made with a vertically split aluminum skin. If an aluminum skin is used, the aluminum bar would probably be unnecessary. The skin would serve the function formerly performed by the bar, that is, causing the gap in the iron to close during cooldown. The aluminum bar would only be needed if the skin could not be made strong enough to take all the preload.

The TAC Style Support

The support structure used by TAC in the superferric magnet is considerably simpler, but uses a different coil geometry. The conductors are arranged in blocks which are horizontally supported by spacer bars. The skin is attached to these bars and preload applied by the differential contraction of the skin during cooldown. Since the magnet is designed for collider operation only, the coil can be solder filled. Mechanically this increases the coil modulus, reducing the displacement necessary to apply sufficient preload and providing for improved self-support of the conductors. The conductor geometry provides for a more efficient reaction of the Lorentz loads by the magnet structure than does a cosO or offset coil geometry.

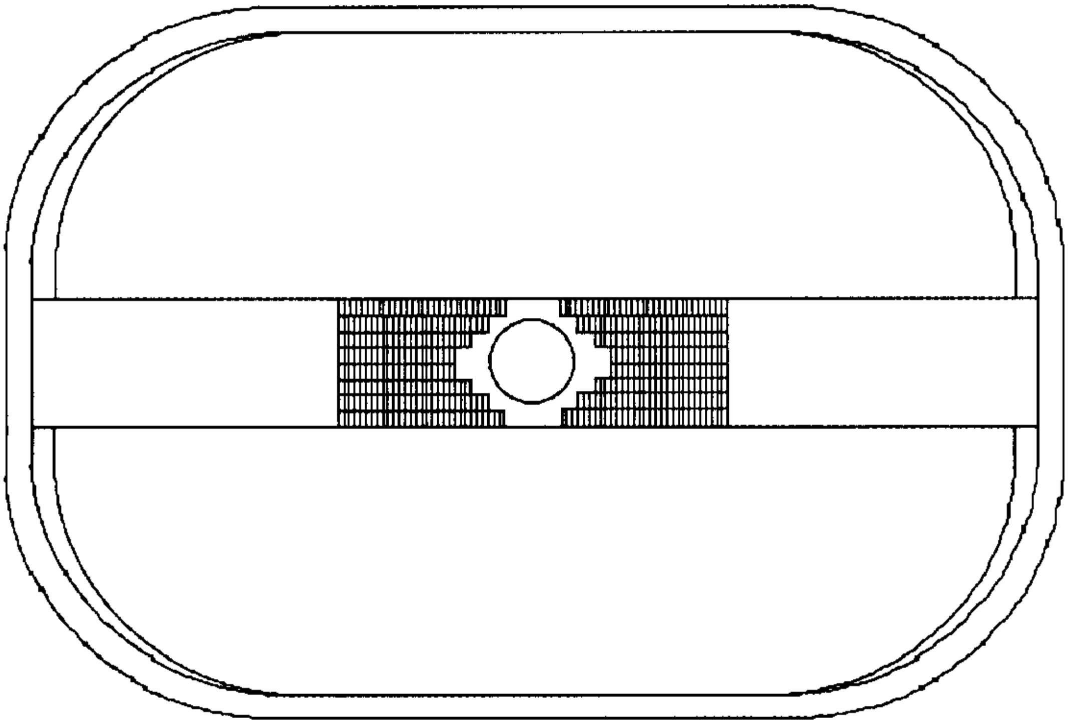


Figure 4. The TAC Style Support

Assembly Procedure for TAC Style System

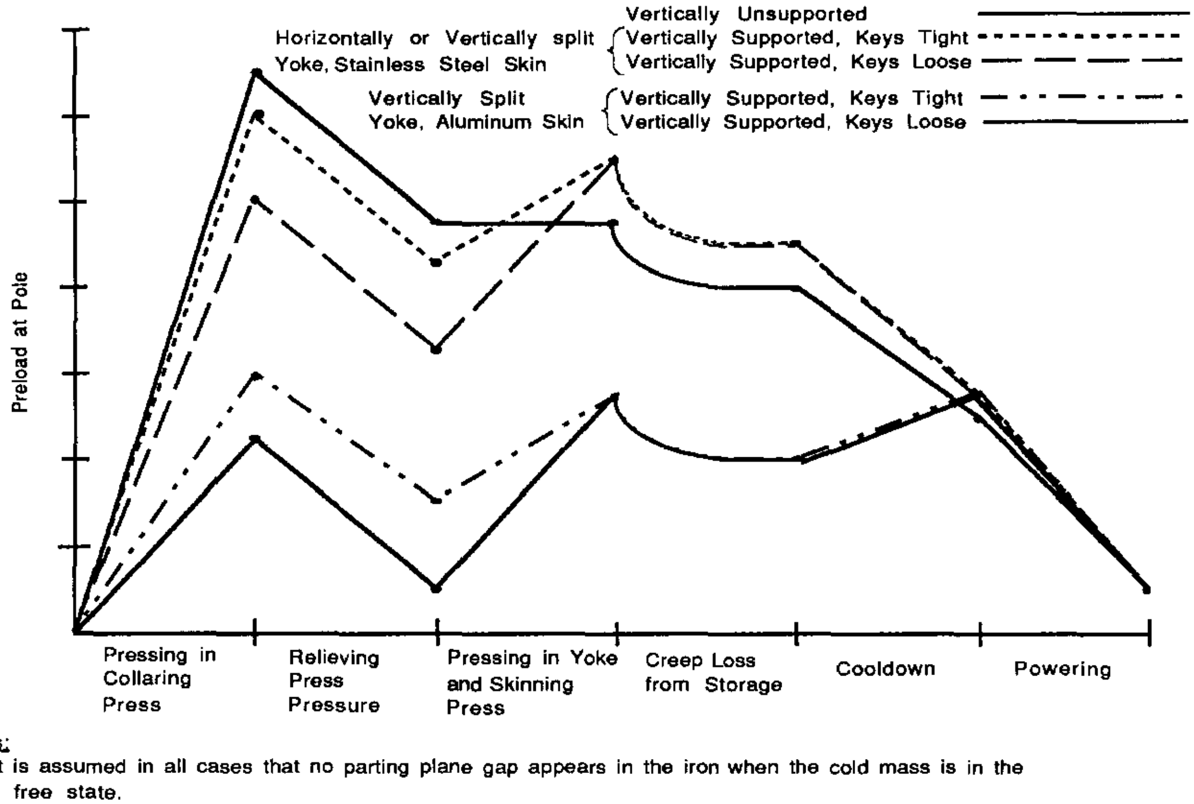
1.) Place Collars on coil.
2.) Place iron on collars.
3.) Press skin until sufficient contact is achieved.
4.) Weld the skin shut.

Preload Losses

When the coil is powered it loses preload at the poles. It may or may not lose preload when it is cooled (depending on the support system). The preload may also change during stages of magnet construction and storage. One of the primary functions of any support system is to provide the coil with preload sufficient so that it will not be unloaded when it is cold and powered. Any of these systems can perform this function. All the systems, however, need to overcompress the coil by an amount which ensures that some preload remains when the magnet is cold and powered. It is desirable that this "overcompression" be as small as possible.

Figures 5 through 8 show the relative preload levels which exist for the various systems from the time the coils are completed until the magnet is powered. The "preload at pole" is shown on the vertical axis. The relative values on this axis can be compared between the various systems although the actual amounts vary with the individual coil size.

The graphs show the final preload (when the magnet is powered) the same in all cases. This allows the reader to compare the relative amounts of "overcompression" necessary for the different support systems.



Notes:

1.) It is assumed in all cases that no parting plane gap appears in the iron when the cold mass is in the warm free state.

2.) It is assumed that the stainlees steel skin with vertically split yoke does not incorporate a gap between the yoke halves when warm.

Figure 5. Horizontally and Vertically Split Yokes

A.) Vertically unsupported collar. The vertically unsupported collar may be used with either a horizontally or vertically split yoke.

- Step 1. Pressing in collaring press. Preload increases as the collar is closed. When the collared coil is closed in the collaring press, preload is very high. This is the only step which involves a preload gain. All the preload is stored during this step.
- Step 2. Relieving press pressure. Preload decreases as collars deflect vertically. Even after deflection the collar is still vertically smaller than the iron cavity into which it will be placed.
- Step 3. Pressing in yoke and skinning press. No preload change. The iron is not compressing the collars vertically.
- Step 4. Creep loss from storage. Stress relaxation in the coils at room temperature causes preload to decrease.
- Step 5. Cooldown. All magnet components contract when cooled. The coil contracts more than the stainless collars causing a preload decrease.
- Step 6. Powering. Magnetic forces cause the coils to move toward the parting plane. The formerly uniform preload distribution changes. The preload increases at the parting plane while decreasing at the pole.

B. Horizontally or Vertically Split Yoke, Vertically supported collar, Stainless steel skin, Keys tight.

- Step 1. Pressing in collaring press. Preload increases as the collar is closed. The initial preload does not have to be as high as in the unsupported case.
- Step 2. Relieving press pressure. Preload decreases as collars deflect. After deflection, the collars are larger vertically than the iron cavity into which they will be placed. Undeflected they would be vertically smaller than the iron cavity.
- Step 3. Pressing in yoke and skinning press. The iron applies a vertical load to the collars as it closes. The preload increases. Coil preload in the yoke and skinning press is lower than it was in the collaring press. Assuming that no parting plane gap appears in the iron, the preload does not decrease significantly when the press pressure is removed.
- Step 4. Creep loss from storage. Stress relaxation in the coils at room temperature causes preload to decrease. Same as unsupported case.

- Step 5. Cooldown. All magnet components contract when cooled. The coil contracts more than the iron, causing a preload decrease. This decrease is greater than in the unsupported case because iron contracts even less than stainless steel when cooled.
- Step 6. Powering. As in the unsupported case, magnetic forces cause the coils to move toward the parting plane. The preload increases at the parting plane while decreasing at the pole. The magnitude of the decrease is greater than in the unsupported case because the yoke presumably does not deflect as much as the collars.

C. Horizontally or Vertically Split Yoke, Vertically supported collar, Stainless steel skin, Collar keys Loose.

- Step 1. Pressing in collaring press. Preload increases as the collar is closed. The initial preload does not have to be as high as in the unsupported or the "keys tight" cases.
- Step 2. Relieving press pressure. Preload decreases as collars deflect. The collars are larger vertically both in the deflected and undeflected states than the iron cavity into which they will be placed.
- Step 3. Pressing in yoke and skinning press. As the iron is closed, it applies a vertical load to the collars. The preload increases. The collar keys come loose. The collars are no longer taking any preload. The preload in the yoke and skinning press is higher than it was in the collaring press. The maximum coil preload exists at this point. Assuming that no parting plane gap appears in the iron, the preload does not decrease significantly when the press pressure is removed.
- Step 4. Creep loss from storage. Stress relaxation in the coils at room temperature causes preload to decrease. Same as unsupported case.
- Step 5. Cooldown. Preload decrease is same as "keys tight" case.
- Step 6. Powering. Preload decrease is same as "keys tight" case.

D. Vertically Split Yoke, Vertically supported collar, Aluminum skin, Keys tight.

- Step 1. Pressing in collaring press. Preload increases as the collar is closed. The initial preload is less than with the stainless skin.
- Step 2. Relieving press pressure. Preload decreases as collars deflect. After deflection, the collars are larger vertically than the iron cavity into which they will be placed. Undeflected, they would be vertically smaller than the iron cavity.

- Step 3. Pressing in yoke and skinning press. As the iron is pressed, it applies a vertical load to the collars. The preload increases. The preload in the yoke and skinning press is lower than it was in the collaring press.
- Step 4. Creep loss from storage. Stress relaxation in the coils at room temperature causes preload to decrease.
- Step 5. Cooldown. All magnet components contract when cooled. The aluminum skin shrinks faster than the coils. Preload increases.
- Step 6. Powering. Preload decrease is same as with stainless skin.

E. Vertically Split Yoke, Vertically supported collar, Aluminum skin, Collar keys Loose.

- Step 1. Pressing in collaring press. Preload increases as the collar is closed. The initial preload does not have to be as high as in the "keys tight" case.
- Step 2. Relieving press pressure. Preload decreases as collars deflect. The collars are larger vertically both in the deflected and undeflected states than the iron cavity into which they will be placed. Same as with stainless skin.
- Step 3. Pressing in yoke and skinning press. As the iron is pressed, it applies a vertical load to the collars. The preload increases. The collar keys come loose. The collars are no longer taking any preload. The preload in the yoke and skinning press is higher than it was in the collaring press. It is uncertain whether the maximum coil preload exists at this point or when the coil is cold and unpowered.
- Step 4. Creep loss from storage. Stress relaxation in the coils at room temperature causes preload to decrease.
- Step 5. Cooldown. Preload increase is same as "keys tight" case with aluminum skin.
- Step 6. Powering. Preload decrease is same as "keys tight" case.

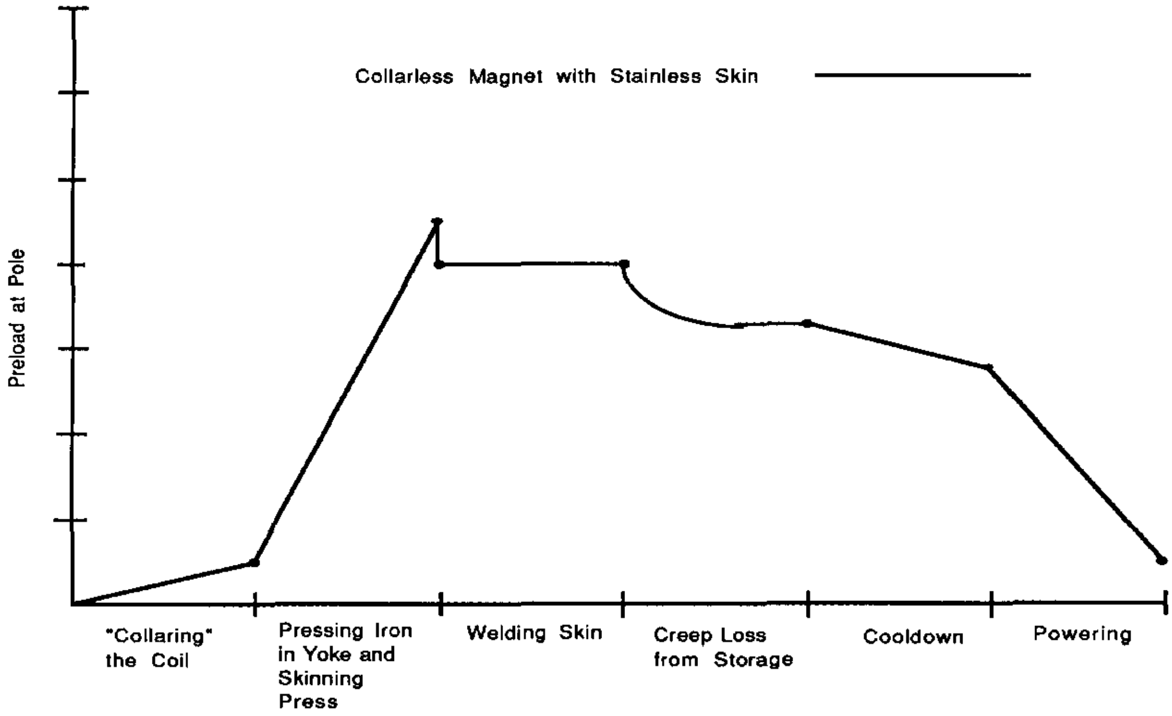


Figure 6. Collarless Magnet with Stainless Skin

F. Collarless magnet with Stainless steel Skin.

- Step 1. "Collaring" the coil. Very little preload is applied as the collars and pole inserts are manually placed on the coils.
- Step 2. Pressing iron in yoke and skinning press. Preload is applied in this step. Slight preload decrease as aluminum bar deflects when press pressure is removed.
- Step 3. Welding skin. When the skin is welded, some of the preload is transferred from the aluminum bar to the stainless steel skin. The total coil preload does not change.
- Step 4. Creep loss from storage. Stress relaxation in the coils at room temperature causes preload to decrease.
- Step 5. Cooldown. The coil contracts. The aluminum bar shrinks, causing the gap in the iron to close and minimizing the preload decrease. The amount that the iron is allowed to close is limited by the rate at which the stainless steel skin contracts.
- Step 6. Powering. Preload decreases as in previous cases.

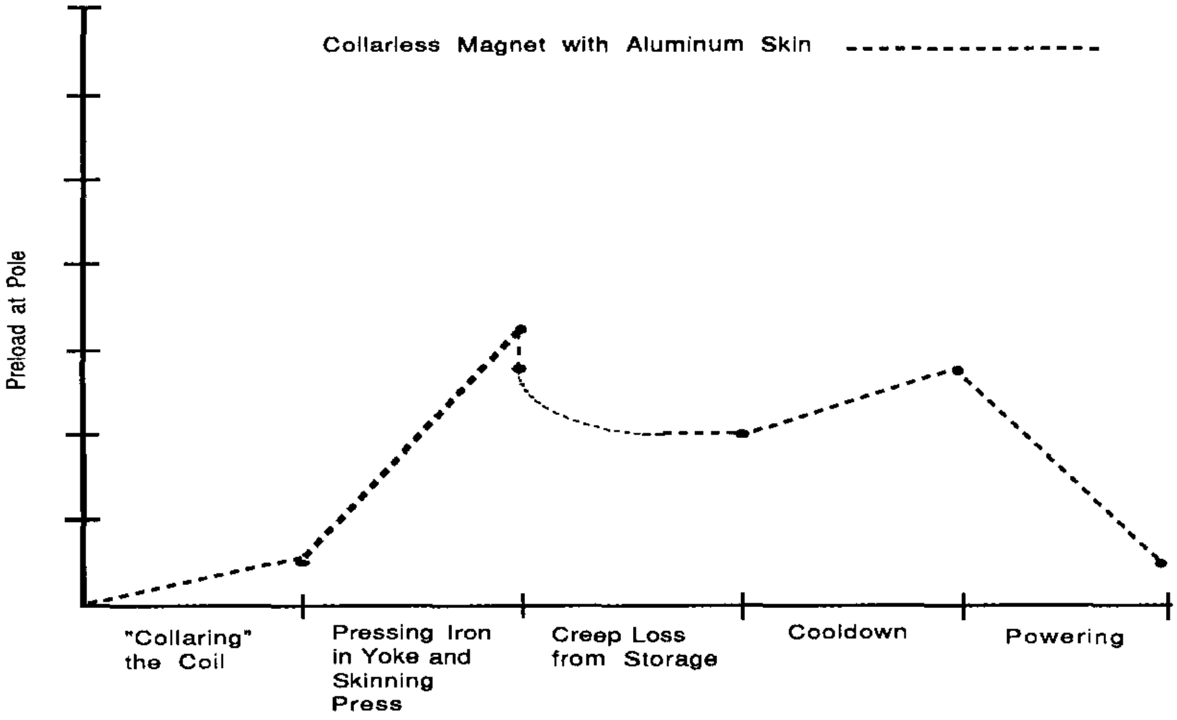


Figure 7. Collarless Magnet With Aluminum Skin

G. Collarless Magnet With Aluminum Skin.

- Step 1. "Collaring" the coil. Very little preload is applied as the collars and pole inserts are manually placed on the coils.
- Step 2. Pressing iron in yoke and skinning press. Preload is applied in this step. Skin is welded. Slight preload decrease as skin deflects when press pressure is removed. Less preload is needed than with the stainless skin.
- Step 3. Creep loss from storage. Stress relaxation in the coils at room temperature causes preload to decrease.
- Step 4. Cooldown. Preload increases as skin shrinks more than coil.
- Step 5. Powering. Preload decreases as in previous cases.

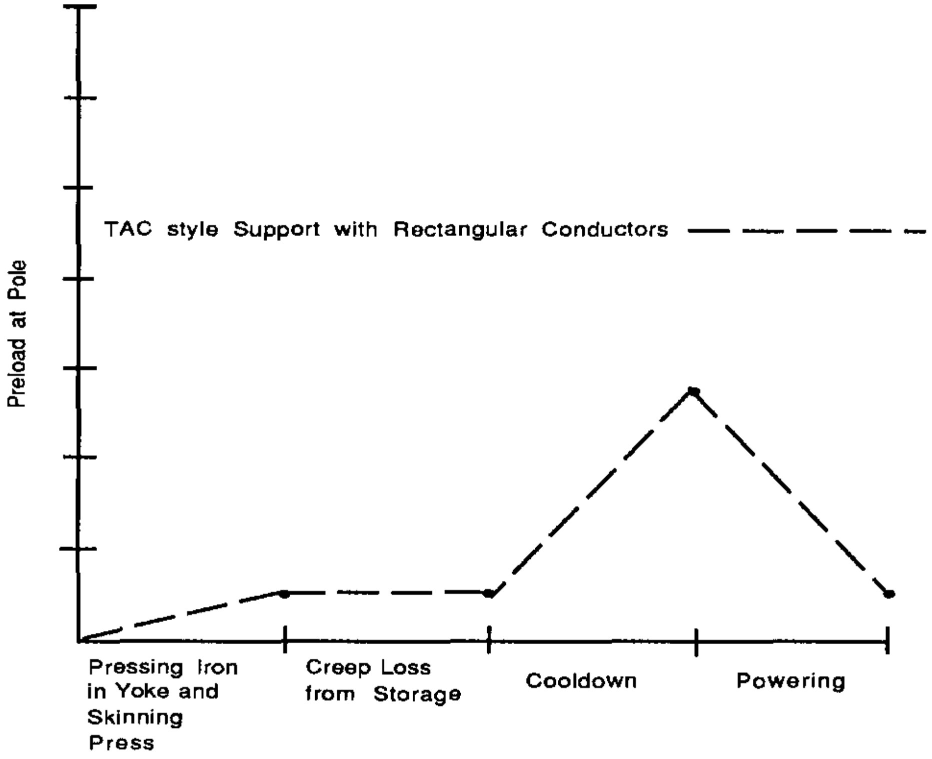


Figure 8. TAC Style Magnet

G. The TAC Style Support.

- Step 1. Pressing iron in yoke and skinning press. Minimal preload is applied in this step. Skin is welded.
- Step 2. Creep loss from storage. Stress relaxation is insignificant because preload is small.
- Step 3. Cooldown. Preload increases as skin shrinks more than coil.
- Step 4. Powering. Preload decreases as in previous cases.

Advantages and Disadvantages of Different Systems

I. Horizontally Split Yoke

- Preload losses high - Peak preload must be very high. Unsupported is worst, followed by supported with keys tight and supported with keys loose.
- Conductor placement variations large and inconsistent from warm to cold. These could be caused by collar deflections if unsupported or parting plane gaps in the iron if supported.
- High stresses may yield skin if collar is supported.
- Assembly procedure is complicated, involving many steps. Two large presses are required. Must overcome differential shrinkage in the horizontal direction between collars and iron when warm.
- Collar/yoke gap could appear at midplane during cooldown.

II. Vertically Split Yoke

- Preload losses same as horizontally split yoke.
- Conductor placement variations small from warm to cold if vertically supported.
- Assembly procedure is complicated, involving many steps. Must overcome differential shrinkage in the vertical direction between collars and iron when warm. This is much larger and more difficult to overcome than that in the horizontal direction.

III. "Collarless" Magnet

- Preload losses are smaller but still significant.
- Conductor placement variations from warm to cold are large but consistent and reproducible from magnet to magnet.
- Assembly is probably simpler. No collaring press is required but an extra operation is needed to insert the aluminum bar. Many parts needed.
- Some iron needs to be removed for the aluminum bar, but it is not in a high field region.
- Many unknowns. Can the aluminum bar be made strong enough to hold its portion of the preload? Can the shrinkages between components be balanced, given size variations in coils and other constituent parts?

Using Aluminum Skin

- Preload losses would be significantly smaller. Much lower stresses after collaring would be needed.
- The skin would have to be very thick. Manufacturing and assembly would be difficult. A very large weld would be needed to attach skin halves to each other.
- Longitudinal differential shrinkage between skin and coil would be increased. A "slip plane" would need to be created between the yoke and skin.

IV. The TAC Style Support.

- Preload losses are extremely low
- Assembly is simple. No large presses would be required.
- Skin might have to be thick. Manufacturing problems could result.
- Coil geometry would have to be different than that which has traditionally been used. The conductors must be solder filled. New technologies would have to be created for production coil winding.
- Ends would be difficult to wind. Current end winding methods are not acceptable for use with this coil geometry.
- The TAC style magnet can be used for collider operation only.

Conclusion

The coil support system serves two primary functions:

1.) Maintain coil preload even when magnet is powered.
2.) Keep conductor placement uniform and repeatable.

Other leading considerations are cost, ease of assembly and manufacturability of components. Many approaches are available. Unanswered questions remain regarding most of the proposed alternatives. One system that has been tested extensively in the Tevatron (totally unsupported, "stand alone" collars) appears to be inadequate for high field magnets. The traditional SSC system (vertically unsupported, horizontally split yoke) requires a large amount of overcompression to maintain preload when coil is powered.

It is not clear which system is the best for each situation. Analysis and testing needs to be done on many of the alternatives to determine what should be used in future magnet designs.

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