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**Mechanical Design and Analysis of the
2D Cross-Section of the
SSC Collider Dipole Magnet**

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INTRODUCTION

This paper describes the mechanical design of the two dimensional cross-section (Figure 1) of the base-line collider dipole magnet for the Superconducting Super Collider. The components described here are the collar laminations (Figure 5, drawing number 0102-ME-292059), the tapered keys that lock the upper and lower collars (Figure 6, drawing number 0102-MB-217851), the yoke laminations (Figure 7, drawing number 0102-ME-292123), the cold mass shell (Figure 8, drawing number 0102-MD-292156).

The collars, made from 21-6-9 stainless steel, are 17 mm wide and have an outer radius of 67.82 mm. They serve to position the conductors at the location specified by the magnetic design[1] and to provide restraint against conductor motion under excitation which might cause the field shape to change or cause premature quenching (training). As in the 40 mm dipoles[2] the upper and lower collars are locked together by tapered keys near the mid-plane and left-right pairs of collars are spot welded to give greater horizontal stiffness. The collars precompress the coil by an amount larger than the sum of the Lorentz ($I \times B$) forces on the conductors and have sufficient bending stiffness by themselves to limit deflections to less than 0.1-0.2 mm under excitation. In addition to being a magnetic element, the yoke is used to provide additional support to the collars near the horizontal mid-plane to limit deflections under the dominantly horizontal Lorentz force. To accomplish this the collars are designed to have a small interference fit (0.08 mm) with the yoke near the horizontal mid-plane at the operating temperature of 4.35 K. The 4.95 mm thick, 340 mm O.D. 304N stainless steel cold mass shell is pretensioned by weld shrinkage to 200-250 MPa at room temperature to firmly clamp the vertically split yoke around the collared coil. Due to the larger thermal contraction of the shell than the yoke the pretension grows to 350-400 MPa with cooldown and provides adequate clamping to restrain the Lorentz force up to fields well above the design operating point. With the collars supported by the yoke the coil deflections under excitation are limited to about 0.02 mm.

We describe in detail below the shape of the outer surface of the collars, which defines the yoke-collar interface, and the shape of the collar interior, which defines the conductor placement. Other features of the collar and yoke will be described in somewhat less detail.

YOKE SPLIT DIRECTION

Because the Lorentz force is mainly horizontal in the body of the magnet, collar deflections are minimized if the yoke supports the collars near

the horizontal mid-plane. The ability to provide this support depends on the relative thermal contractions of the yoke and collar materials, the choice of yoke split direction and the details of the relative shapes of the collar outer surface and the yoke inner surface. The collars are made of 21-6-9 stainless steel which has an integrated thermal contraction[3] to 4 K of -2.9×10^{-3} and the yoke is made of low carbon steel which has an integrated thermal contraction[3] of -2.1×10^{-3} . To be inserted easily into the yoke at room temperature the collar diameter in the direction of the yoke split must be no larger than the yoke inner diameter. During cooldown the collars shrink more than the yoke and may lose contact with the yoke along the split direction.

If the yoke is split in the horizontal direction, the collared coil must be sufficiently vertically oversized that when clamped in the yoke it deflects horizontally to contact the yoke when cold. (See Figure 2a.) This design is sensitive to the magnet-to-magnet variation in collared coil vertical diameter due to prestress variation. The measured rate of deflection in the 40 mm dipoles is about 0.004 mm/MPa resulting in an expected range of 0.1-0.15 mm in vertical diameter for a preload range of ± 20 MPa. Finite element calculations for the 50 mm dipole give a similar sensitivity. These calculations indicate that if there is sufficient vertical interference between the yoke and collars to ensure horizontal contact for the lowest preload coils, the mid-plane will be open by 0.05-0.1 mm at liquid helium temperature for the highest preload coils. Alternatively, if the vertical yoke-collar interference is reduced to guarantee that the yoke gap is closed for the highest prestress coils, then for the low prestress coils horizontal yoke-collar contact will be lost at 4 K and the collars will be less well supported. At room temperature a mid-plane gap is likely to exist for all coils.

In contrast, the collared coil horizontal diameter is relatively insensitive to coil prestress. (The vertical force from the coil prestress is applied at a smaller radius than the opposing force for the keys. This couple causes an inward bending of the sides of the collars that almost perfectly cancels the outward deflection due to the internal pressure of the coils.[4]) Finite element calculations and measurements[4] of 40 mm SSC dipoles show that the rate of horizontal deflection is less than 20% of that in the vertical direction; the horizontal diameter varies by < 0.03 mm for the full range of expected coil preloads. If a vertically split yoke design is adopted it is relatively easy to ensure both good horizontal support to the collared coil and a closed mid-plane gap independent of the coil preload. This can be achieved with the larger thermal contraction collar material by appropriately choosing the horizontal and vertical diameters of the collars. In this case (Figure 2b) the collared coil is oversize in the horizontal direction and undersize in the vertical direction to allow easy insertion into the yoke for even the highest preload coils. Under cooldown the collars move away from the yoke at the vertical radius but positive contact is maintained at the horizontal radius. At zero field, the shell azimuthal tension is balanced primarily by a pressure between the mating surfaces of the yoke halves. As the field increases, the mid-plane progressively unloads as the horizontal Lorentz force is transferred to the yoke. Figure 3 shows the forces for the 50 mm design discussed below. As long as

the shell tension exceeds the Lorentz force, the mid-plane gap remains closed and the yoke behaves as a rigid solid structure. Several 40 mm dipoles have been built and tested with a vertically split yoke and have performed as expected[5,6].

Based on the considerations above a vertically split yoke design has been chosen for the base-line 50 mm collider dipole magnet. Because this design has not been tested as extensively as the horizontally split case used for most 40 mm SSC dipoles, a backup 50 mm design with a horizontally split yoke is being built at BNL. The latter will not be described here.

DESIGN OBJECTIVES

The gross features of the yoke, in particular the inner and outer radii, are set by the magnetic design[1]. Other detailed features, for example the placement of the cooling channels and the holes for yoke-pack assembly pins, are set by a combination of mechanical and magnetic considerations. The major design objectives discussed in this section have to do with the yoke-collar and yoke-yoke interfaces and with the collar interior surface. For the yoke-collar and yoke-yoke interfaces the design should satisfy the following:

- 1) The yoke and collar should be in contact at the horizontal mid-plane at 4 K and zero field. A small positive loading of ≥ 100 N/mm should be present to guarantee good transverse and axial restraint over the full excitation range. The close collar-yoke-shell fit causes the axial Lorentz force to be transferred the shell and limits the compressive loading of the coil end.
- 2) Yoke mid-plane gap should be closed under all circumstances at $T = 4$ K up to at least $B = 8$ T (20% in field and 45% in force above the operating point).
- 3) If possible, the yoke mid-plane gap should also be closed at assembly at room temperature; requirements (1) and (2) takes precedence, however.

The combination of collar deflections due to coil prestress, assembly into the yoke and cooldown must result in a coil of the design shape: round, at the correct radius and with the correct pole angles. The "target shape" for the coils, fully assembled at 4 K and zero field, is the shape specified by the magnetic design shrunk according to the thermal contraction of stainless steel. This would be the shape of the coils if the collars were infinitely rigid. Prestress causes the vertical radius to increase, yoke assembly causes the horizontal radius to decrease and the vertical radius to increase, and cooldown causes both to decrease with the vertical decreasing somewhat more. The interior surface of the undeflected collar at room temperature must therefore have a horizontal radius larger and a vertical radius smaller than nominal to arrive at the correct shape cold. (See Figure 4.)

YOKE COLLAR INTERFACE

A simple spring model was used to model the interaction among the collar, yoke, and shell and to check the sensitivity of the system to uncertainties in the parameters of the calculation and part tolerances. Values of the parameters were derived from finite element calculations described in Reference 7 and from measurements on 40 mm SSC dipoles. The precise collar dimensions used in the finite element analysis differed by up to 0.09 mm from the final dimension chosen here.

The calculation models the collars as coupled vertical and horizontal springs with effective spring constants and vertical-horizontal couplings for forces applied by coil prestress and shell tension. Because the collars are designed so that they always clear the yoke in the vertical direction, the model is insensitive to parameters relevant to the vertical radius. The finite stiffness of the yoke is not explicitly included, but since the effective spring constants come from finite element calculations that include yoke elastic properties, these effects are implicitly included. The parameters of the calculation are shown in Table Ia and the source of their values are given below.

rv and rh The vertical and horizontal collar radii relative to the yoke at room temperature are chosen to give the desired yoke-collar interaction and varied to check the effect of parts tolerances.

Shell Stress The azimuthal shell stress at 300 K and 4 K is based on measurements made at Fermilab on model magnets F3[8] and DSS012[9] and at LBL on the first QC cross section 40 mm quadrupole.[10] The shell stress near the yoke parting plane determines the clamping force and this was measured to be 175-200 MPa at room temperature and 300-350 MPa at 4 K. The low end of the range was used in both cases. In fact, the model calculates the shell tension required to close the mid-plane gap at both temperatures, so the effect of varying the shell tension can be easily seen. The measurements in References 8-10 indicate that the parting plane stress comes from the weld shrinkage and is at or near the room temperature yield strength of the shell material in the annealed state. The 50 mm aperture models will use a higher strength material 304N specified to have a minimum yield strength of 310 MPa. An analysis of the shell tension, including frictional effects and the interaction with the tooling[11,12], indicates that with the use of 304N the shell stress at the mid-plane is expected to be > 210 MPa under the most pessimistic assumptions consistent with data[11]. At 4 K the shell tension should be > 350 MPa.

Thermal Contraction The integrated thermal contraction of the collar and the yoke material was measured[3] at BNL to be -2.9×10^{-3} and -2.1×10^{-3} respectively. Standard tables[13] give values of -3.0×10^{-3} and -2.0×10^{-3} for stainless steel and iron. Both sets of values were tried; the final values are based on an average of the two with their difference representing the uncertainty from this source.

Nominal Radius This is the yoke inner radius for the magnetic design[1] of the W6733 cross section.

drv/drh The ratio of vertical to horizontal radius change for a horizontal force applied by the yoke was copied from the 40 mm model[14,15]. Because of the similarity of the 40 mm and 50 mm designs, the value of drv/drh should be similar. Variations of $\pm 10\%$ about the central value were tried. Since this effects only the vertical yoke-collar clearance it is if little importance for this design.

drv/dpr and drh/dpr The rate of change of collar vertical and horizontal radius with prestress (average of inner and outer coils) was taken from finite element calculations[7,16] and measurements of 40 mm magnets.[17] The finite element results depend on whether or not the wedges are allowed to slide relative to the adjacent conductors:

	drv/dpr	drh/dpr	
slip[7]	1.4×10^{-3}	-1.8×10^{-4}	mm/MPa
no slip[16]	1.7×10^{-3}	-0.7×10^{-4}	mm/MPa

Measured[17] vertical deflections of 40 mm collars, 2.0×10^{-3} mm/MPa, are somewhat larger than predicted by finite element calculations[14] 1.6×10^{-3} mm/MPa. Values of drv/dpr from 1.3 to 1.9×10^{-3} mm/MPa and of drh/dpr from 0 to -0.4×10^{-3} mm/MPa were tried. Because there is no vertical yoke-collar interaction and the values of drh/dpr are small, the results are not very sensitive to these variations.

Prestress The target collared coil room temperature prestress is approximately 70 MPa. A range of ± 20 MPa, somewhat larger than is expected, was tried.

Cooldown Prestress Loss To simplify the calculation of the effects of cooldown, the model separately cools the collared coil and the yoke, and then assembles them cold. This procedure is valid because the system is linear and elastic. The prestress loss with cooldown used in the model is that for a free collared coil. This has been measured in 40 mm magnets[18] to be approximately 17 and 14 MPa for the inner and outer coils respectively. Values of 15.5 and 22.5 MPa (average of inner and outer coils) were tried. Because of the similarity of the designs, the behavior of the 50 mm dipole is expected to be similar. Since this affects mainly the collared coil vertical radius it is not a very important parameter.

drh/d(Shell Stress) The rate of change of collared coil vertical radius with shell tension has two values depending on whether the collars are free to expand vertically or not. Because the collars always clear the yoke, only the first (larger) value is important. Its value, -1.0×10^{-3} mm/MPa, is taken from finite element calculations[7] and is varied between -0.9 and 1.2×10^{-3} mm/MPa.

The results of the calculations are shown in Tables Ib-e. Tables Ib-d use the recent BNL[3] values of integrated thermal contraction. The three tables correspond to three values of collar horizontal radius representing the estimated range of 0.15 ± 0.05 mm of horizontal yoke collar interference (see below). Table Ie uses the same collar dimensions as Table Ic but shows the effect of a larger difference in yoke and collar thermal contractions. In each table the first line represents the "central values" of the parameters, which are then varied, as indicated by comments in the tables, in subsequent lines. For each set of

parameters the vertical and horizontal radii of the free collared coil relative to the yoke are computed at both room temperature and 4 K. The central values of the results quoted below are an average of the central values in Tables Ic and Ie.

The room temperature yoke-collar interference in the horizontal direction is $0.14 \pm 0.05 \pm 0.004 \pm 0.004$ mm, where the first error bar is from parts tolerances, the second is from prestress variation and the third is from uncertainties in the calculation parameters. The horizontal yoke-collar interference is $0.08 \pm 0.05 \pm 0.005 \pm 0.02$ mm at 4 K. The room temperature vertical clearances before and after assembly are $0.33 \pm 0.05 \pm 0.03 \pm 0.01$ and $0.25 \pm 0.05 \pm 0.03 \pm 0.02$ mm. The vertical clearance at 4 K is about 0.1 mm larger than at 300 K.

The shell tension required to make the collar horizontal radius equal the yoke radius, that is to close the yoke mid-plane gap, is $130 \pm 50 \pm 7 \pm 20$ MPa at room temperature and $80 \pm 50 \pm 5 \pm 20$ MPa at 4 K. With a shell stress of approximately 200 MPa at room temperature the yoke gap may be barely closed under the least favorable conditions, but it is closed with a $> 50\%$ margin for the central values of the parameters. At 4 K the shell stress is ≥ 350 MPa; of this $270 \pm 50 \pm 5 \pm 20$ MPa is balanced by the pressure at the yoke mating surface and is therefore available to balance the Lorentz force. With the 4.95 mm thick shell, this is a force of $1340 \pm 250 \pm 25 \pm 100$ N/mm per quadrant. The lower bound is approximately equal to the Lorentz force of 890 N/mm per quadrant at full field. Finite element calculations[7] indicate that the collars are sufficiently stiff that only about 45% of the force is transferred to the yoke, so this design has more than a 100% margin against yoke gap opening even under the most pessimistic assumption and the yoke gap should stay closed to 10 T.

COLLAR OUTER SURFACE

The calculations above require a horizontal interference between the yoke and the undeflected collar at room temperature of 0.15 mm and vertical clearance of > 0.27 mm. The shape of the collar outer surface (Figure 5) provides for interference between 0 and 30° and clearance between 30° and 90° . In both regions the collar radius is 0.01 mm larger than the yoke inner radius (Figure 6). (The intent was to make them equal but due to minor design errors a 0.01 mm discrepancy resulted.) Over the 0 to 30° range the center of curvature is displaced horizontally by 0.14 mm to generate the 0.15 mm interference and between 30° and 90° the center is displaced vertically by 0.46 mm to generate a vertical clearance of 0.45 mm, comfortably larger than is required. A small step occurs at the transition as shown in detail G of the collar drawing, Figure 5.

The tolerances that effect the yoke collar interface are those on the radius and horizontal offset of the collar outer surface and the radius and offset (relative to the yoke mating surface) of the yoke inner radius. Each is set to be ± 0.012 mm. This value is chosen as being the best that can be achieved with current lamination stamping technology. The combined tolerance on the horizontal yoke-collar interference is ± 0.05 mm as used in the calculations above. Tolerances of dimensions effecting the clearance between 30° and 90° are similar, but since the clearance is always > 0.10 mm, these tolerances are less important.

Table Ia

 ***** Collared Coil In Vertically Split Yoke *****

----- Input Parameters -----
 rv(Rv) = collar(yoke) vertical radius - nominal radius (mm)
 rh(Rh) = collar(yoke) horizontal radius - nominal radius (mm)
 skin_stress = azimuthal skin stress at 4 K (MPa)
 skin_stress_300K = azimuthal skin stress at 300 K (MPa)
 contract_coilar = integrated thermal contraction to 4 K of collar material
 contract_yoke = integrated thermal contraction to 4 K of yoke material
 r_nominal = nominal 300 K unstressed collar radius (mm)
 drv/drh = drv/drh for horizontal force
 drv/dpr = drv/d(prestress) (average of inner and outer) (mm/MPa)
 drh/dpr = drh/d(prestress) (average of inner and outer) (mm/MPa)
 prestr = free collared coil prestress at 300 K (average of inner and outer) (MPa)
 dcool = free collared coil cooldown prestress change (average of inner and outer) (MPa)
 dh/ds1 = drh/d(skin stress) rv < Rv (mm/MPa)
 dh/ds2 = drh/d(skin stress) rv > Rv (mm/MPa)

----- Output Parameters -----
 rv = rv-Rv of free collared coil (mm)
 rh = rh-Rh of free collared coil (mm)
 rh_rv0 = rh-Rh for rv = Rv (mm)
 rv_rh0 = rv-Rv for rh = Rh (mm)
 rh_sk = rh-Rh for assumed skin stress (mm)
 rv_sk = rv-Rv for assumed skin stress (mm)
 sk_rv0 = skin stress to make rv = Rv (MPa)
 sk_rh0 = skin stress to make rh = Rh (MPa)

 ***** 50 mm Dipole *****

Table Ib

```

-----
r_nominal      =  67.82 mm
rv             =  -0.44 mm
rh            =   0.10 mm
skin_stress_300K = 175.00 MPa
skin_stress    = 300.00 MPa
contract_collar = -2.00 * 1.E-3
contract_yoke  = -2.10 * 1.E-3
-----

```

														----- T = 300 K -----				----- T = 4 K -----			
drv/drh	drv/dpr	drh/dpr	prestr	dcool	dh/ds1	dh/ds2	rh	rv	rv_rh0	sk_rh0	rh	rv	rh_rv0	rv_rh0	rh_sk	rv_sk	sk_rv0	sk_rh0			
-0.55	0.0017	-0.0002	70.0	-15.5	-.00100	-.00011	0.09	-0.32	-0.27	86.	0.03	-0.40	-0.70	-0.38	0.00	-0.30	-	35.			
-0.55	0.0013	-0.0002	90.0	-15.5	-.00100	-.00011	0.08	-0.32	-0.28	82.	0.03	-0.40	-0.69	-0.38	0.00	-0.30	-	31.			
----- Vary Coil Prestress and Cooldown Loss -----																					
-0.55	0.0017	-0.0002	90.0	-15.5	-.00100	-.00011	0.08	-0.29	-0.24	82.	0.03	-0.37	-0.64	-0.35	0.00	-0.35	-	31.			
-0.55	0.0017	-0.0002	50.0	-15.5	-.00100	-.00011	0.09	-0.35	-0.31	90.	0.04	-0.44	-0.75	-0.41	0.00	-0.41	-	39.			
-0.55	0.0017	-0.0002	70.0	-22.5	-.00100	-.00011	0.09	-0.32	-0.27	86.	0.04	-0.41	-0.72	-0.39	0.00	-0.39	-	36.			
----- Vary dr/d(prestress) -----																					
-0.55	0.0013	-0.0002	70.0	-15.5	-.00100	-.00011	0.09	-0.35	-0.30	86.	0.03	-0.42	-0.73	-0.40	0.00	-0.40	-	35.			
-0.55	0.0015	-0.0002	70.0	-15.5	-.00100	-.00011	0.09	-0.34	-0.29	86.	0.03	-0.41	-0.72	-0.39	0.00	-0.39	-	35.			
-0.55	0.0019	-0.0002	70.0	-15.5	-.00100	-.00011	0.09	-0.31	-0.26	86.	0.03	-0.39	-0.68	-0.37	0.00	-0.37	-	35.			
-0.55	0.0017	0.0000	70.0	-15.5	-.00100	-.00011	0.10	-0.32	-0.27	100.	0.05	-0.40	-0.68	-0.38	0.00	-0.38	-	46.			
-0.55	0.0017	-0.0004	70.0	-15.5	-.00100	-.00011	0.07	-0.32	-0.28	72.	0.02	-0.40	-0.71	-0.39	0.00	-0.39	-	24.			
----- Choose values that give a small and a big collared coil (vertically) -----																					
-0.55	0.0013	-0.0002	50.0	-22.5	-.00100	-.00011	0.09	-0.38	-0.33	90.	0.04	-0.46	-0.79	-0.44	0.00	-0.44	-	40.			
-0.55	0.0019	-0.0002	90.0	-15.5	-.00100	-.00011	0.08	-0.27	-0.22	82.	0.03	-0.35	-0.61	-0.34	0.00	-0.34	-	31.			
----- Choose values that give a small and a big collared coil (horizontally) -----																					
-0.55	0.0017	-0.0004	90.0	-15.5	-.00100	-.00011	0.06	-0.29	-0.25	64.	0.02	-0.37	-0.65	-0.36	0.00	-0.36	-	16.			
-0.55	0.0017	0.0000	70.0	-15.5	-.00100	-.00011	0.10	-0.32	-0.27	100.	0.05	-0.40	-0.68	-0.38	0.00	-0.38	-	46.			
----- Vary dr/d(skin stress) -----																					
-0.55	0.0017	-0.0002	70.0	-15.5	-.00080	-.00009	0.09	-0.32	-0.27	100.	0.03	-0.40	-0.70	-0.38	0.00	-0.38	-	44.			
-0.55	0.0017	-0.0002	70.0	-15.5	-.00100	-.00011	0.09	-0.32	-0.27	86.	0.03	-0.40	-0.70	-0.38	0.00	-0.38	-	35.			
-0.55	0.0017	-0.0002	70.0	-15.5	-.00120	-.00013	0.09	-0.32	-0.27	72.	0.03	-0.40	-0.70	-0.38	0.00	-0.38	-	29.			
----- Vary drv/drh -----																					
-0.50	0.0017	-0.0002	70.0	-15.5	-.00100	-.00011	0.09	-0.32	-0.28	86.	0.03	-0.40	-0.77	-0.38	0.00	-0.38	-	35.			
-0.60	0.0017	-0.0002	70.0	-15.5	-.00100	-.00011	0.09	-0.32	-0.27	86.	0.03	-0.40	-0.63	-0.38	0.00	-0.38	-	35.			

Table Ic

```

-----
r_nominal      = 67.82 mm
rv             = -0.44 mm
rh             = 0.15 mm
skin_stress_300K = 175.00 MPa
skin_stress    = 300.00 MPa
contract_collar = -2.90 * 1.E-3
contract_yoke  = -2.10 * 1.E-3
-----

```

											T = 300 K				T = 4 K			
drv/drh	drv/dpr	drh/dpr	prestr	dcool	dh/ds1	dh/ds2	rh	rv	rv_rh0	sk_rh0	rh	rv	rh_rv0	rv_rh0	rh_sk	rv_sk	sk_rv0	sk_rh0
-0.55	0.0017	-0.0002	70.0	-15.5	-.00100	-.00011	0.14	-0.32	-0.25	136.	0.08	-0.40	-0.65	-0.35	0.00	-0.35	-	85.
-0.55	0.0013	-0.0002	90.0	-15.5	-.00100	-.00011	0.13	-0.32	-0.25	132.	0.08	-0.40	-0.64	-0.35	0.00	-0.35	-	81.
----- Vary Coil Prestress and Cooldown Loss -----																		
-0.55	0.0017	-0.0002	90.0	-15.5	-.00100	-.00011	0.13	-0.29	-0.21	132.	0.08	-0.37	-0.59	-0.32	0.00	-0.32	-	81.
-0.55	0.0017	-0.0002	50.0	-15.5	-.00100	-.00011	0.14	-0.35	-0.28	140.	0.09	-0.44	-0.70	-0.39	0.00	-0.39	-	89.
-0.55	0.0017	-0.0002	70.0	-22.5	-.00100	-.00011	0.14	-0.32	-0.25	136.	0.09	-0.41	-0.67	-0.37	0.00	-0.37	-	86.
----- Vary dr/d(prestress) -----																		
-0.55	0.0013	-0.0002	70.0	-15.5	-.00100	-.00011	0.14	-0.35	-0.27	136.	0.08	-0.42	-0.68	-0.38	0.00	-0.38	-	85.
-0.55	0.0015	-0.0002	70.0	-15.5	-.00100	-.00011	0.14	-0.34	-0.26	136.	0.08	-0.41	-0.67	-0.37	0.00	-0.37	-	85.
-0.55	0.0019	-0.0002	70.0	-15.5	-.00100	-.00011	0.14	-0.31	-0.23	136.	0.08	-0.39	-0.63	-0.34	0.00	-0.34	-	85.
-0.55	0.0017	0.0000	70.0	-15.5	-.00100	-.00011	0.15	-0.32	-0.24	150.	0.10	-0.40	-0.63	-0.35	0.00	-0.35	-	90.
-0.55	0.0017	-0.0004	70.0	-15.5	-.00100	-.00011	0.12	-0.32	-0.25	122.	0.07	-0.40	-0.66	-0.36	0.00	-0.36	-	74.
----- Choose values that give a small and a big collared coil (vertically) -----																		
-0.55	0.0013	-0.0002	50.0	-22.5	-.00100	-.00011	0.14	-0.38	-0.30	140.	0.09	-0.46	-0.74	-0.41	0.00	-0.41	-	90.
-0.55	0.0019	-0.0002	90.0	-15.5	-.00100	-.00011	0.13	-0.27	-0.20	132.	0.08	-0.35	-0.56	-0.31	0.00	-0.31	-	81.
----- Choose values that give a small and a big collared coil (horizontally) -----																		
-0.55	0.0017	-0.0004	90.0	-15.5	-.00100	-.00011	0.11	-0.29	-0.22	114.	0.07	-0.37	-0.60	-0.33	0.00	-0.33	-	60.
-0.55	0.0017	0.0000	70.0	-15.5	-.00100	-.00011	0.15	-0.32	-0.24	150.	0.10	-0.40	-0.63	-0.35	0.00	-0.35	-	90.
----- Vary dr/d(skin stress) -----																		
-0.55	0.0017	-0.0002	70.0	-15.5	-.00000	-.00000	0.14	-0.32	-0.25	170.	0.08	-0.40	-0.65	-0.35	0.00	-0.35	-	100.
-0.55	0.0017	-0.0002	70.0	-15.5	-.00100	-.00011	0.14	-0.32	-0.25	136.	0.08	-0.40	-0.65	-0.35	0.00	-0.35	-	85.
-0.55	0.0017	-0.0002	70.0	-15.5	-.00120	-.00013	0.14	-0.32	-0.25	113.	0.08	-0.40	-0.65	-0.35	0.00	-0.35	-	71.
----- Vary drv/drh -----																		
-0.50	0.0017	-0.0002	70.0	-15.5	-.00100	-.00011	0.14	-0.32	-0.25	136.	0.08	-0.40	-0.72	-0.36	0.00	-0.36	-	95.
-0.60	0.0017	-0.0002	70.0	-15.5	-.00100	-.00011	0.14	-0.32	-0.24	136.	0.08	-0.40	-0.58	-0.35	0.00	-0.35	-	85.

Table Id

```

-----
r_nominal      = 67.82 mm
rv             = -0.44 mm
rh            = 0.20 mm
skin_stress_300K = 175.00 MPa
skin_stress    = 300.00 MPa
contract_collar = -2.90 * 1.E-3
contract_yoke  = -2.10 * 1.E-3
-----

```

																T = 300 K				T = 4 K							
drv/drh	drv/dpr	drh/dpr	prestr	dcool	dh/ds1	dh/ds2	rh	rv	rv_rh0	sk_rh0	rh	rv	rh_rv0	rv_rh0	rh_sk	rv_sk	sk_rv0	sk_rh0									
-0.55	0.0017	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.19	-0.32	-0.22	186.	0.13	-0.40	-0.60	-0.33	0.00	-0.33	-	-	135.								
-0.55	0.0013	-0.0002	90.0	-15.5	-0.00100	-0.00011	0.18	-0.32	-0.22	182.	0.13	-0.40	-0.59	-0.33	0.00	-0.33	-	-	131.								
----- Vary Coil Prestress and Cooldown Loss -----																											
-0.55	0.0017	-0.0002	90.0	-15.5	-0.00100	-0.00011	0.18	-0.29	-0.19	182.	0.13	-0.37	-0.54	-0.30	0.00	-0.30	-	-	131.								
-0.55	0.0017	-0.0002	50.0	-15.5	-0.00100	-0.00011	0.19	-0.35	-0.25	190.	0.14	-0.44	-0.65	-0.36	0.00	-0.36	-	-	139.								
-0.55	0.0017	-0.0002	70.0	-22.5	-0.00100	-0.00011	0.19	-0.32	-0.22	186.	0.14	-0.41	-0.62	-0.34	0.00	-0.34	-	-	136.								
----- Vary dr/d(prestress) -----																											
-0.55	0.0013	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.19	-0.35	-0.25	186.	0.13	-0.42	-0.63	-0.35	0.00	-0.35	-	-	135.								
-0.55	0.0015	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.19	-0.34	-0.23	186.	0.13	-0.41	-0.62	-0.34	0.00	-0.34	-	-	135.								
-0.55	0.0019	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.19	-0.31	-0.20	186.	0.13	-0.39	-0.58	-0.32	0.00	-0.32	-	-	135.								
-0.55	0.0017	0.0000	70.0	-15.5	-0.00100	-0.00011	0.20	-0.32	-0.21	200.	0.15	-0.40	-0.58	-0.32	0.00	-0.32	-	-	140.								
-0.55	0.0017	-0.0004	70.0	-15.5	-0.00100	-0.00011	0.17	-0.32	-0.23	172.	0.12	-0.40	-0.61	-0.33	0.00	-0.33	-	-	124.								
----- Choose values that give a small and a big collared coil (vertically) -----																											
-0.55	0.0013	-0.0002	50.0	-22.5	-0.00100	-0.00011	0.19	-0.38	-0.27	190.	0.14	-0.46	-0.69	-0.38	0.00	-0.38	-	-	140.								
-0.55	0.0019	-0.0002	90.0	-15.5	-0.00100	-0.00011	0.18	-0.27	-0.17	182.	0.13	-0.35	-0.51	-0.28	0.00	-0.28	-	-	131.								
----- Choose values that give a small and a big collared coil (horizontally) -----																											
-0.55	0.0017	-0.0004	90.0	-15.5	-0.00100	-0.00011	0.16	-0.29	-0.20	164.	0.12	-0.37	-0.55	-0.30	0.00	-0.30	-	-	116.								
-0.55	0.0017	0.0000	70.0	-15.5	-0.00100	-0.00011	0.20	-0.32	-0.21	200.	0.15	-0.40	-0.58	-0.32	0.00	-0.32	-	-	146.								
----- Vary dr/d(skin stress) -----																											
-0.55	0.0017	-0.0002	70.0	-15.5	-0.00080	-0.00009	0.19	-0.32	-0.22	233.	0.13	-0.40	-0.60	-0.33	0.00	-0.33	-	-	109.								
-0.55	0.0017	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.19	-0.32	-0.22	186.	0.13	-0.40	-0.60	-0.33	0.00	-0.33	-	-	135.								
-0.55	0.0017	-0.0002	70.0	-15.5	-0.00120	-0.00013	0.19	-0.32	-0.22	155.	0.13	-0.40	-0.60	-0.33	0.00	-0.33	-	-	112.								
----- Vary drv/drh -----																											
-0.50	0.0017	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.19	-0.32	-0.23	180.	0.13	-0.40	-0.67	-0.33	0.00	-0.33	-	-	135.								
-0.60	0.0017	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.19	-0.32	-0.21	180.	0.13	-0.40	-0.53	-0.32	0.00	-0.32	-	-	135.								

Table Ia

```

-----
r_nominal      =  67.62 mm
rv             =  -0.44 mm
rh            =   0.15 mm
skin_stress_300K = 175.00 MPa
skin_stress    = 300.00 MPa
contract_collar = -3.00 * 1.E-3
contract_yoke  = -2.00 * 1.E-3
-----

```

----- T = 300 K -----											----- T = 4 K -----								
drv/drh	drv/dpr	drh/dpr	prestr	dcool	dh/ds1	dh/ds2	rh	rv	rv_rh0	sk_rh0	rh	rv	rh_rv0	rv_rh0	rh_sk	rv_sk	sk_rv0	sk_rh0	
-0.55	0.0017	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.14	-0.32	-0.25	136.	0.07	-0.42	-0.68	-0.38	0.00	-0.38	-	71.	
-0.55	0.0013	-0.0002	90.0	-15.5	-0.00100	-0.00011	0.13	-0.32	-0.25	132.	0.07	-0.41	-0.68	-0.37	0.00	-0.37	-	67.	
----- Vary Coil Prestress and Cooldown Loss -----																			
-0.55	0.0017	-0.0002	90.0	-15.5	-0.00100	-0.00011	0.13	-0.29	-0.21	132.	0.07	-0.38	-0.63	-0.34	0.00	-0.34	-	67.	
-0.55	0.0017	-0.0002	50.0	-15.5	-0.00100	-0.00011	0.14	-0.35	-0.28	140.	0.08	-0.45	-0.74	-0.41	0.00	-0.41	-	75.	
-0.55	0.0017	-0.0002	70.0	-22.5	-0.00100	-0.00011	0.14	-0.32	-0.25	136.	0.07	-0.43	-0.70	-0.39	0.00	-0.39	-	73.	
----- Vary dr/d(prestress) -----																			
-0.55	0.0013	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.14	-0.35	-0.27	136.	0.07	-0.44	-0.72	-0.40	0.00	-0.40	-	71.	
-0.55	0.0015	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.14	-0.34	-0.26	136.	0.07	-0.43	-0.70	-0.39	0.00	-0.39	-	71.	
-0.55	0.0019	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.14	-0.31	-0.23	136.	0.07	-0.40	-0.66	-0.37	0.00	-0.37	-	71.	
-0.55	0.0017	0.0000	70.0	-15.5	-0.00100	-0.00011	0.15	-0.32	-0.24	150.	0.08	-0.42	-0.67	-0.37	0.00	-0.37	-	82.	
-0.55	0.0017	-0.0004	70.0	-15.5	-0.00100	-0.00011	0.12	-0.32	-0.25	122.	0.06	-0.42	-0.69	-0.38	0.00	-0.38	-	66.	
----- Choose values that give a small and a big collared coil (vertically) -----																			
-0.55	0.0013	-0.0002	50.0	-22.5	-0.00100	-0.00011	0.14	-0.38	-0.30	140.	0.08	-0.47	-0.78	-0.43	0.00	-0.43	-	77.	
-0.55	0.0019	-0.0002	90.0	-15.5	-0.00100	-0.00011	0.13	-0.27	-0.20	132.	0.07	-0.37	-0.66	-0.33	0.00	-0.33	-	67.	
----- Choose values that give a small and a big collared coil (horizontally) -----																			
-0.55	0.0017	-0.0004	90.0	-15.5	-0.00100	-0.00011	0.11	-0.29	-0.22	114.	0.05	-0.38	-0.64	-0.35	0.00	-0.35	-	52.	
-0.55	0.0017	0.0000	70.0	-15.5	-0.00100	-0.00011	0.15	-0.32	-0.24	150.	0.08	-0.42	-0.67	-0.37	0.00	-0.37	-	82.	
----- Vary dr/d(skin stress) -----																			
-0.55	0.0017	-0.0002	70.0	-15.5	-0.00080	-0.00009	0.14	-0.32	-0.25	170.	0.07	-0.42	-0.68	-0.38	0.00	-0.38	-	89.	
-0.55	0.0017	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.14	-0.32	-0.25	136.	0.07	-0.42	-0.68	-0.38	0.00	-0.38	-	71.	
-0.55	0.0017	-0.0002	70.0	-15.5	-0.00120	-0.00013	0.14	-0.32	-0.25	113.	0.07	-0.42	-0.68	-0.38	0.00	-0.38	-	59.	
----- Vary drv/drh -----																			
-0.50	0.0017	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.14	-0.32	-0.25	136.	0.07	-0.42	-0.76	-0.38	0.00	-0.38	-	71.	
-0.60	0.0017	-0.0002	70.0	-15.5	-0.00100	-0.00011	0.14	-0.32	-0.24	136.	0.07	-0.42	-0.62	-0.37	0.00	-0.37	-	71.	

COLLAR INNER SURFACE

The interior shape of the collar determines the conductor placement which in turn determines the field shape. The "target shape" for the coils, fully assembled at 4 K and zero field, is the shape specified by the magnetic design shrunk according to the thermal contraction of stainless steel. The design method begins with a collar which, in its undeflected state at room temperature, has the dimensions given by the magnetic design. Finite element calculations[7] are done to determine the net deflection of the collar due to assembly and cooldown. The deflections returned by the finite element calculations include both mechanical deflections due to the stresses on the collar and the thermal contraction of the stainless steel from which the collar is made. The difference between the shape of the undeflected collar at 4 K (which is the target shape) and final shape from the finite element calculations is determined. This difference is then added to the appropriate dimensions of the original (nominal) collar design. The result is a shape which, after all deflections have occurred, has the correct shape at 4 K.

The nominal collar shape was determined by taking the profile of the insulated conductors from the magnetic design (Figure 9, drawing MB-292000) and adding to it the nominal thickness of the ground wrap insulation. (See Figure 10, drawing MB-292047. All Kapton layers and the strip heater package are 0.13 mm thick and the collaring shoe is 0.38 mm thick.) It is specified by the radii of the inner surfaces of the collar (the outer surface of the outer coil plus ground wrap and collaring shoe, the outer surface of the inner coil plus ground wrap and the inner surface of the inner coil) and the distance from the vertical center line of the intersections of the inner and outer coil pole surfaces plus ground wrap with the collar surfaces at the inner and outer coil radii. These dimensions are shown in Table II.

Table II
Nominal Collar Shape From the Magnetic Design
(all dimensions are mm)

Location	r	x	y
Outer Midplane	50.76	50.76	0.00
Outer Pole Outer Edge	50.76	34.19	37.52
Outer Pole Inner Edge	37.84	23.94	29.30
Inner Pole Outer Edge	37.84	9.88	36.53
Inner Pole Inner Edge	24.78	5.86	24.08

Finite element calculations were performed for the case in which both the inner and the outer coil prestresses were 70 MPa and the horizontal yoke-collar interference was 0.17 mils. The net deflection to 4 K of five points on the interior of the collar were tabulated. The results are shown in Table III.

In Table IV these deflections are compared with the deflections due to thermal contraction of stainless steel alone. An integrated thermal contraction to 4 K of -3.0×10^{-3} is assumed here as was the finite element model. These are shown in the columns labeled "Thermal Contraction". The differences between the total deflection and the thermal contraction are displayed in the next two columns labeled "Deflection rel. to free collar at 4K". These are the

deflections of the collars at 4 K due to mechanical stresses. These are then corrected for the fact that the design calls for 0.15 mm of horizontal yoke-collar interference while the finite element calculations assumed 0.17 mm. The correction is done by adding 0.02 mm to the x deflection at the horizontal mid-plane and decreasing the other x deflections by the same proportion. The y deflection nearest to the pole is decreased by 0.01 mm. (The vertical radius changes by about minus one-half the change in horizontal radius for a horizontally applied force. See the section on the yoke-collar interface.) The other y deflections are decreased by the same proportion. The results are in the columns labeled "Corr. to design yoke-collar interference".

Table III
Collar displacements (mm) due to assembly and cooldown

Location	dx	dy
Outer Midplane	-0.26	0.00
Outer Pole Outer Edge	-0.12	-0.03
Outer Pole Inner Edge	-0.09	0.03
Inner Pole Outer Edge	-0.04	0.01
Inner Pole Inner Edge	-0.02	0.05

Table IV
Corrected Collar Deflections (mm)

Location	Thermal Contraction		Deflection rel. to free collar at 4K		Corr. to design yoke-collar interference	
	dx	dy	dx	dy	dx	dy
Outer Midplane	-0.15	0.00	-0.11	0.00	-0.09	0.00
Outer Pole Outer Edge	-0.10	-0.11	-0.02	0.09	-0.02	0.08
Outer Pole Inner Edge	-0.07	-0.09	-0.02	0.12	-0.01	0.11
Inner Pole Outer Edge	-0.03	-0.11	0.00	0.12	0.00	0.11
Inner Pole Inner Edge	-0.02	-0.07	0.00	0.12	0.00	0.11

The desired collar shape, undeflected at room temperature, is gotten by subtracting dx and dy in the last two columns in Table IV from the x and y coordinates in Table II. This sets the coordinates at the five locations listed. The rest of the collar surfaces are made circular with radii and centers chosen to pass through these five points. Because the cable width is preserved by the deflections, the radii must all be changed by the same amount and they must remain concentric. The radii are increased by 0.09 mm to generate the required increase in x at the horizontal mid-plane. The centers of curvature are offset vertically by -0.20 mm relative to the horizontal center line. This value was chosen to give the best fit to the design values of y-dy at the design values of x+dx from Tables II and IV. In the collar drawing (Figure 5) the radius r and center offset of each surface and the distance 2x between corresponding corners on the left and right sides are specified. (Note that in the coordinate system defined in this discussion positive y is down on the collar drawing.) Table V shows the values of r, offset and x and the values of y at the corners derived from them. It also shows the differences between

the y values so generated and those derived from y and dy in Tables II and IV.

Table V
Design Collar Dimensions (mm)

Location	r	offset	x	y	y-deviation
Outer Midplane	50.85	-0.20	50.85	0.00	-
Outer Pole Outer Edge	50.85	-0.20	34.21	37.42	-0.02
Outer Pole Inner Edge	37.93	-0.20	23.95	29.21	0.02
Inner Pole Outer Edge	37.93	-0.20	9.88	36.42	0.01
Inner Pole Inner Edge	24.87	-0.20	5.86	23.97	0.00

The coordinates that actually appear on the collar drawing differ from these by a small amount for several reasons. First, the original calculations on the basis of which the drawing was originally made assumed 0.14 mm of horizontal yoke-collar interference rather than 0.15 mm. The 0.01 mm discrepancy is the same one mentioned in the discussion of the collar outer surface. Second, the original calculation was done based on an earlier cross-section which differed from the one currently in use by up to 0.2 mm due to changes in the cable dimensions. The collar drawing was corrected for these cross section changes but the calculations discussed in this paper were not redone. For reasons not understood additional discrepancies up to 0.05 mm have appeared from this cause. Table VI shows the actual coordinates from the drawing. The numbers in parentheses are the differences between the actual values and those in Table V. The discrepancies are all very small, the largest being a displacement of the outer coil pole surface azimuthally towards the mid-plane by 0.06 mm.

Table VI
Actual Collar Dimensions (mm)

Location	r	offset	x	y
Outer Midplane	50.83(-.02)	-0.18(.02)	50.83(-.02)	-
Outer Pole Outer Edge	50.83(-.02)	-0.18(.02)	34.25(0.04)	37.38(-.04)
Outer Pole Inner Edge	37.92(-.01)	-0.18(.02)	24.00(0.05)	29.18(-.03)
Inner Pole Outer Edge	37.92(-.01)	-0.18(.02)	9.88(0.00)	36.43(0.01)
Inner Pole Inner Edge	24.87(0.00)	-0.18(.02)	5.85(-.01)	23.99(0.01)

OTHER COLLAR FEATURES

The small tab on the side of the collar (detail A, Figure 5) is used to center the collared coil vertically in the yoke. It has a $\pm 8.5^\circ$ taper to ease insertion into the yoke. The flats on the side of the collar and the yoke in the region of the tapered keys are, in the undeflected parts, at the identical distance from the vertical center-line. However, because of the 0.15 mm mils of interference just above the tapered keys, after assembly the collars are deflected so that there is 0.15 ± 0.08 mm of clearance between the yoke and collars at the base of the alignment tab. The lower bound of the tolerance

band on the yoke slot width is equal to the upper bound of that on the collar tab. However, because the collar is displaced 0.15 mm radially inwards at assembly, there is a clearance of between 0.01 and 0.06 mm on either side of the alignment tab for the full range of the relevant part tolerances. This may allow the coil to be vertically off-center in the yoke by up to ± 0.06 mm, which will in turn generate a skew quadrupole moment a_1 of up to ± 0.6 units[19]. In fact, it is unlikely that the parts tolerances will conspire so as to give this maximum allowable vertical clearance over the entire manufacturing run so the expected contribution to $\sigma(a_1)$ is considerably smaller than this. (The effect on other harmonics of vertical off-centering is negligible[19] with respect to their specified tolerances.)

The slots for the tapered keys (detail A of Figure 5) are 0.30 mm larger than the tapered keys themselves (Figure 7). Only the "upper" surfaces of the key slots on the drawing contact the keys so a considerable tighter tolerance (0.02 mm) has been specified for them than for the opposite surfaces. The "active" surfaces have been placed so that for nominal dimensions the center lines of the upper and lower collars are coincident. The key slots are oversized for two reasons: 1) to ease insertion of the keys if the keys are placed rather than driven into the slots ("square key" method) and 2) to allow, by procurement of slightly larger keys, for up to 0.03 mm of "anti-ovalization" if it is decided to drive the keys into the slots ("tapered key" method). The latter process has been observed[16] in 40 mm magnets to result in an additional vertical deflection of the collars of 0.03-0.05 mm on the radius due to scoring of the keys or local yielding of the collars near the key slots. It is currently planned to use the square key method, but both the tooling and the collar + key design allow use of the tapered key method.

The small notches in the outer surface are used for lifting the collared coil assembly in either "upright" or 90° rotated orientations. (The later is required for insertion into the vertically-split yoke) and for azimuthal alignment within the collaring tooling. The notch on the outer surface at the pole is for routing instrumentation wires. Its width and placement are not particularly important for the collar design but tighter tolerances have been applied as this is the most convenient datum to define the vertical center line for inspection.

OTHER YOKE FEATURES

As noted above the yoke inner and outer radii are part of the magnetic design[1]. Most other features effect the saturation characteristics of the magnet so, although their sizes and locations are set mostly by mechanical considerations, magnetic effects were also considered. The square hole on the horizontal mid-plane is used to control the effect of iron saturation on b_2 and its size and location was chosen[1] based on the magnetic effects of the other features.

The cooling channel diameter of 29.1 mm was copied from the 40 mm magnet. The precise size that is desirable from a cryogenic system standpoint depends somewhat on the magnet cooling method. The size was set before the cooling method was chosen and is believed to be sensible[20] if the beam pipe is small enough to allow about 10% of the helium flow to go through the beam tube annulus. Presently the beam tube annular space is only 1.6 mm allowing only 1-2% of the helium to flow near the coil. Therefore larger cooling channels may be appropriate in the final design.

The bus slot and the cooling channels have been set to the largest radius at which they will fully clear the 19 mm wide end clamp filler pack (Figure 11, drawing MD-292141) which is used to support the shell at the end of the magnet. The cooling channel is placed as close to the vertical center-line as possible while still maintaining enough material between it and the bus slot to ensure the mechanical integrity of the lamination.

Four 12.88 mm diameter holes are used for pins to make yoke packs. The two nearer the horizontal center-line are placed at as large a radius possible and the others are placed as close to the vertical parting plane as possible to minimize their effects on iron saturation.

The notch at the outer radius at the vertical parting plane interlocks with the alignment key (Figure 12, drawing MB-292155). The alignment key interlocks to the yoking tooling to hold the magnet in a straight, twist-free state as the shell is welded, and it also serves as a fiducial feature for later alignment of the cold mass in the cryostat. As such the tolerance on the yoke notch and alignment key are name quite tight (0.025 mm full range on the key width and on the slot full width). The tolerance bands are set so that the fit between the yoke and the key varies from 0 to 0.05 mm clearance. At the yoke radius of 165.05 mm this implies an angular uncertainty of 0.3 mrad. The depth of the notch and the thickness of the key are set so that at minimum clearance the shoulder of the key is flush with the corner of the yoke notch and at maximum clearance it is 0.10 mm below the yoke.

REFERENCES

1. R.C. Gupta, S.A. Kahn and G.H. Morgan, "SSC 50 mm Dipole Cross Section," submitted to the 3rd International Industrial Symposium on Super Collider, Atlanta, GA, March 13-15, 1991.
2. A. Devred, et al., "Status of 4-cm Aperture, 17-m-Long SSC Dipole Magnet R&D Program at BNL Part I: Magnet Assembly," submitted to the 3rd International Industrial Symposium on the Supercollider, Atlanta, GA, March 13-15, 1991.
3. C. L. Goodzeit, "Structural Response of DSX201 Yoke and Shell (and Vertically Split Version) to Thermal and Lorentz Loads," 4/23/90 (unpublished).
4. C.L. Goodzeit and P. Wanderer, "Summary of Construction Details and Test Performance of Recent Series of 1.8 Meter SSC Dipoles at BNL," Proceedings of the Second International Industrial Symposium of the Super Collider, 743 (1990) M. McAshan, ed.
5. J. Strait, et al., "Experimental Evaluation of Vertically Versus Horizontally Split Yokes for SSC Dipole Magnets," Proceedings of the Second International Industrial Symposium of the Super Collider, 731 (1990) M. McAshan, ed.
6. W. Koska, et al., "Tests of 40 mm SSC Dipole Model Magnets with Vertically Split Yokes," submitted to the 1991 IEEE Particle Accelerator Conference, San Francisco, CA, May 6-9, 1991.

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10. C. Taylor, *LBL Quadrupole Program, Minutes of the MSIM*, 6/12/90.
11. J. Strait, *Analysis of Yoke-Skin Interaction*, TS-SSC 90-040, 6/28/90.
12. J. Strait, *Evaluation of Yoking Tooling Design*, TS-SSC 90-059, 9/10/90.
13. Brookhaven National Laboratory Selected Cryogenic Data Notebook, BNL 10200-R, August, 1980, J.E. Jensen, et al., eds.
14. J. Cortella, private communications. Some of the relevant finite element calculation results for the 40 mm dipole are summarized in Ref. 16.
15. J. Strait, *Design of a Vertically-Split Yoke and Associated Collar for the 40 mm Dipole*, TS-SSC 90-029, 6/11/90.
16. J. R. Turner, *Mechanical Analysis of the W6733H Cross Section*, SSCL Magnet Systems Division internal note MD-TA-143.
17. J. Strait, *Notes on Collared Coil Mechanics and Sextupole Moment*, Minutes of the MSIM, 7/11-12/90.
18. J. Strait, *Calculation of Desired Vertical Ovality of SSC Collars*, Minutes of the MSIM, 10/10-11/89.
19. A. Mokhtarani, *Effect of Manufacturing Errors on Harmonics in 5 cm SSC Magnets*, TS-SSC 91-038, 1/7/91.
20. M. McAshan, private communication.

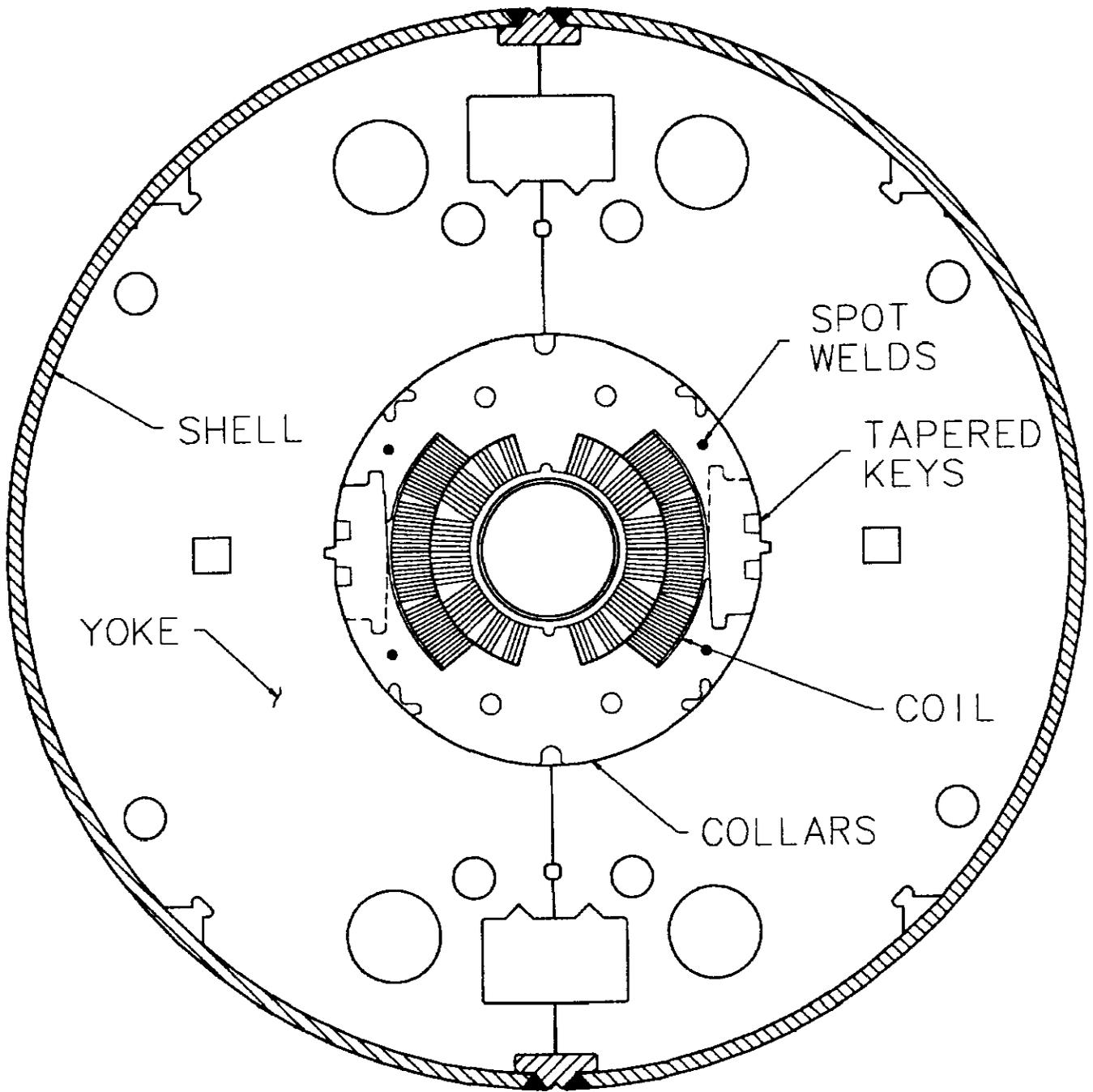


Figure 1
SSC Collider Dipole Magnet Cross Section

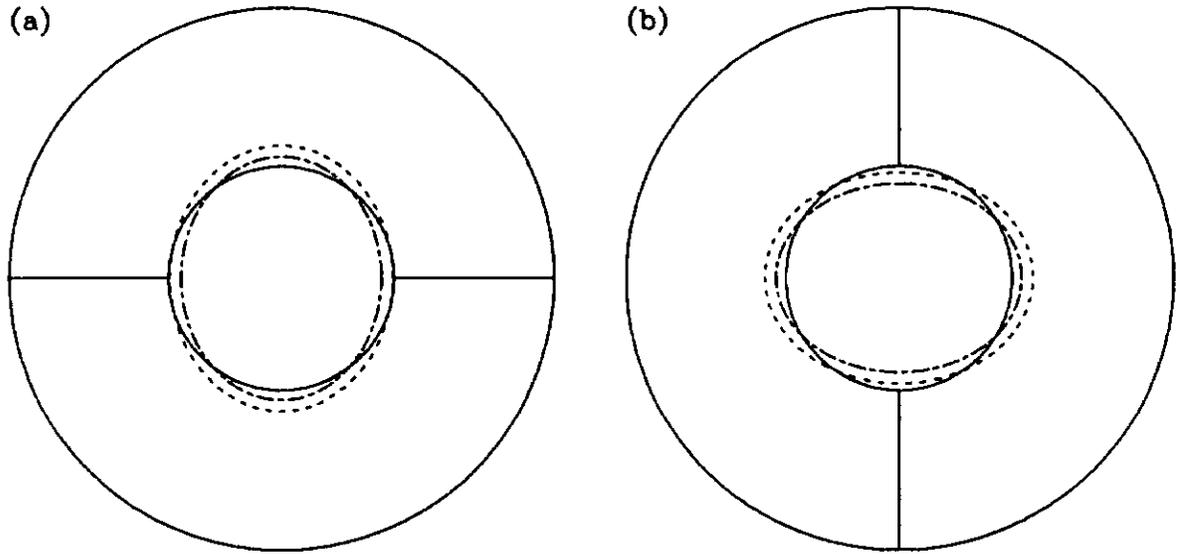


Figure 2
Horizontally split (a) and vertically split (b) yoke configurations. The solid lines represent the yoke laminations, the dotted lines represent the free collared coil at $T=300$ K and the dot-dashed lines represent the free collared coil at $T=4$ K. (The collared coil distortions relative to the yoke are greatly exaggerated.)

Forces on Half Yoke and Skin (N/mm)

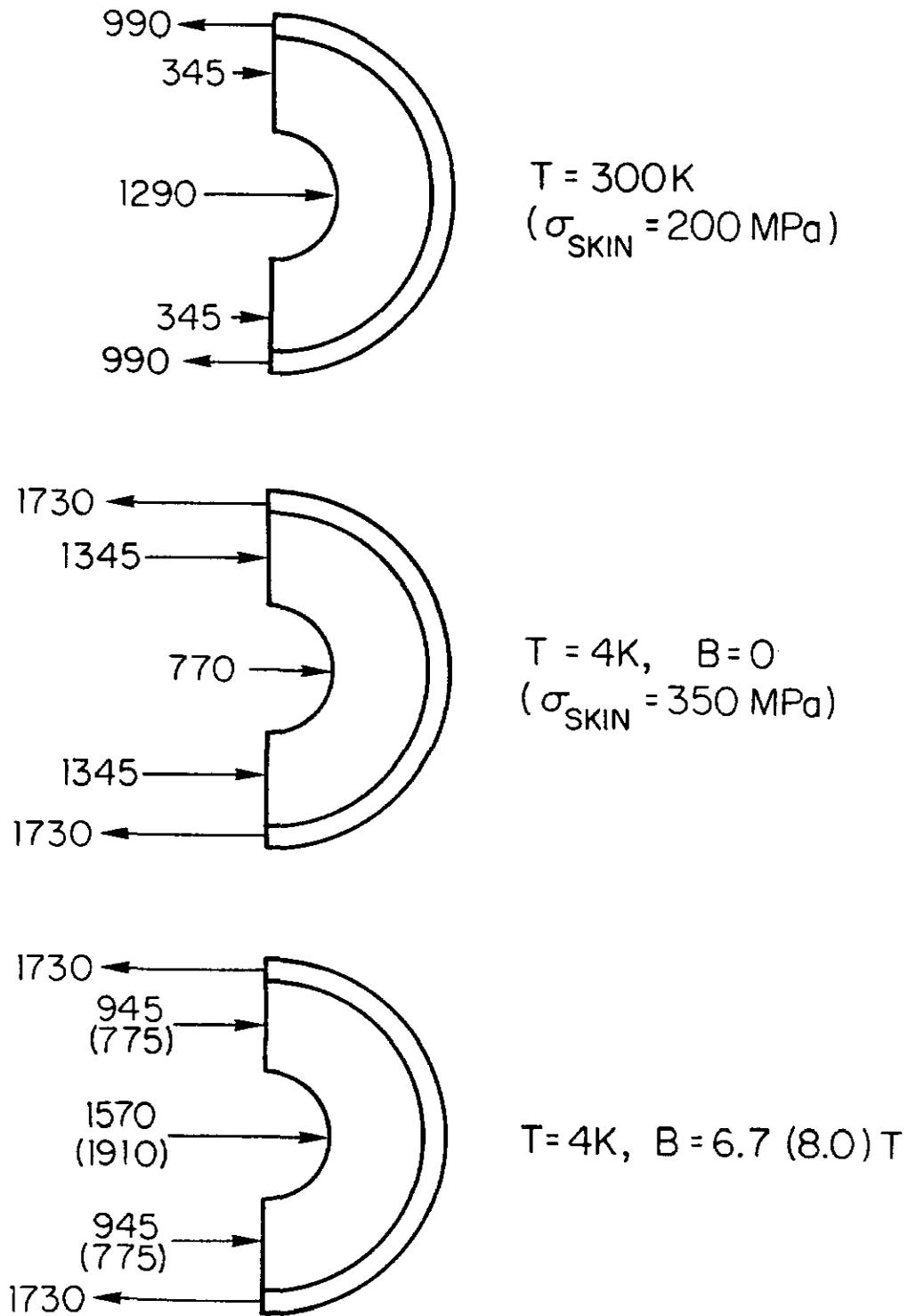


Figure 3

Forces (N/mm) on the a half yoke and shell due to shell azimuthal stress, yoke-yoke parting plane pressure, and the reaction of the collared coil. The force due to the collared coil includes the elastic effects of the yoke-collar interference fit and of the Lorentz force.

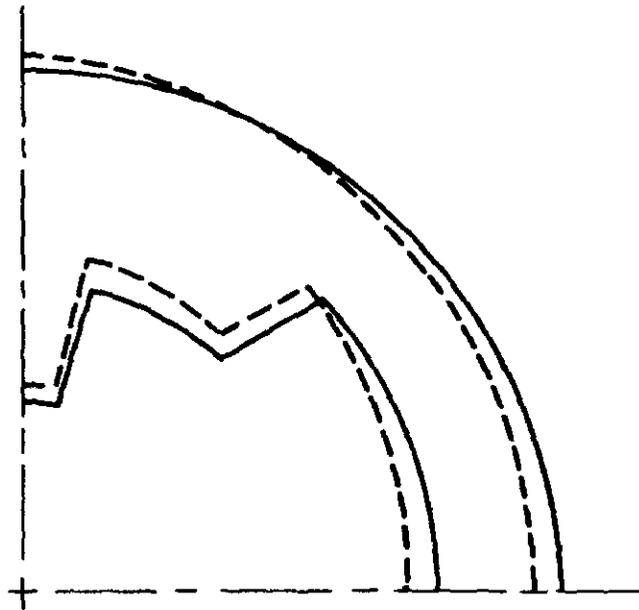
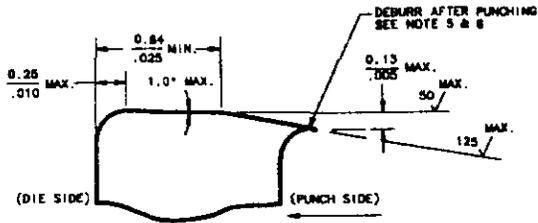


Figure 4
Relation between the free (solid line) and deflected (dashed-line) collar at 4 K.

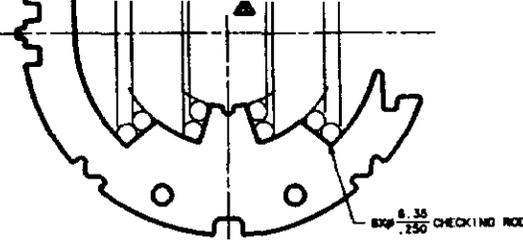
DETAIL C

SCALE 4 : 1

RE TO INTERSECTIONS AS SHOWN

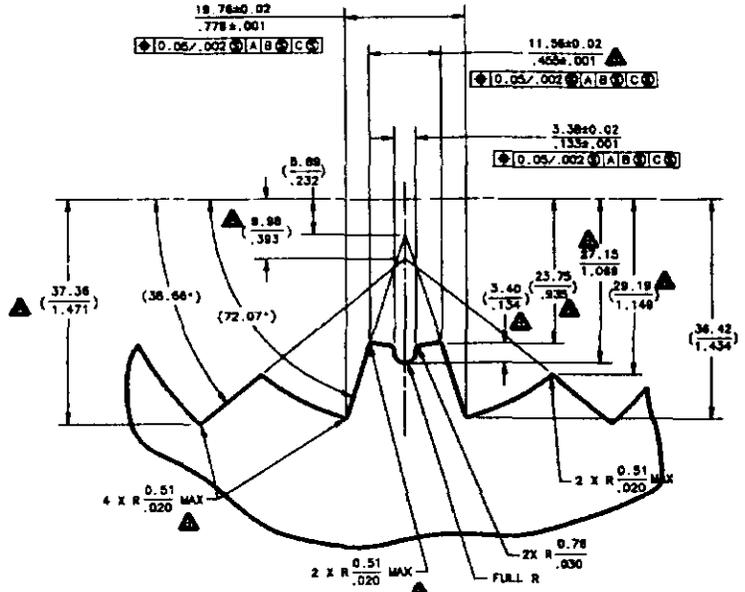


PUNCH EDGE BEFORE DEBURRING

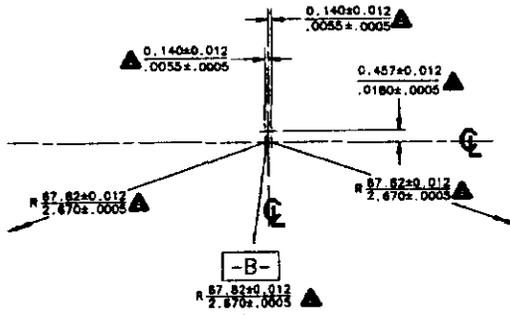
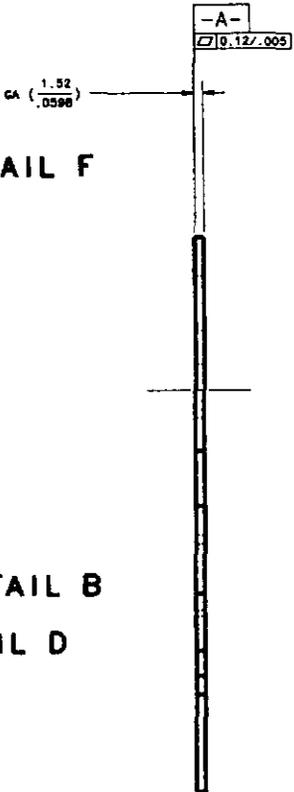


REFERENCE BALL DIMS.

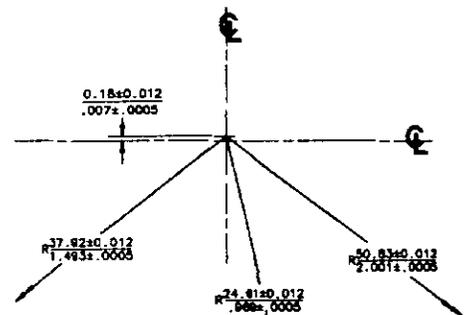
SCALE 1 : 1



DETAIL D



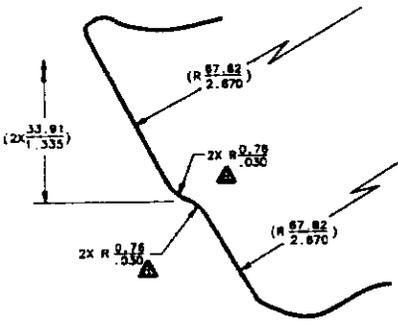
OUTER RADIUS DIMENSION LOCATIONS



INNER RADIUS DIMENSION LOCATIONS

DETAIL F

SCALE: 4 to 1



DETAIL G

SCALE: 8 to 1

Figure 5b

NOTES:

- 1-MATERIAL: #16GA. (.0598)NITRONIC-40 ASTM A-412 GR.XM-11.
- 2-ALL DIMENSIONS ARE TO TRUE CORNER INTERSECTIONS
- 3-DIMENSIONS SHOWN ARE ON DIE SIDE.
- 4-TOLERANCES ARE NON-CUMULATIVE.
- 5-TUMBLE TO REMOVE ALL SHARP EDGES AND BURRS.
- 6-FINISHED LAM. MUST BE FREE OF ALL FOREIGN MATTER, OIL, GREASE, METAL PARTICLES, ETC. PRODUCED DURING DIE PUNCHING OR TUMBLING.
- 7-THIS COLLAR IS MADE TO BE USED WITH VERTICALLY SPLIT YOKE LAMINATION #0102-ME-292123
- 8-ALL TOLERANCES ±.12mm (.005 inch) UNLESS OTHERWISE SPECIFIED; ANGLES ±.25°.

ITEM	PART NO.	DESCRIPTION OR SIZE	QTY.
PARTS LIST			
UNLESS OTHERWISE SPECIFIED:			
1. ALL DIMENSIONS ARE IN MILLIMETERS.	ORIGINATOR	J. STRAIT	
2. TOLERANCES SEE NOTE 8.	DRAWN	RICK DIXON	5/23/90
3. DIMENSIONS BASED UPON ANSI Y14.2M-1992	CHECKED	J. Brandt	7/17/90
4. INCH DIMENSIONS ARE FOR REFERENCE ONLY.	APPROVED	R. Bossert	7/17/90
5. BREAK ALL SHARP EDGES	USED ON		
6. DO NOT SCALE DRAWING.	MATERIAL	SEE NOTE 1	
7. MAX. ALL MACH. SURFACES 125 / MILLIMETER / INCH			
8. DIMENSION IDENTIFICATION: MILLIMETER / INCH			
FERMILAB NATIONAL ACCELERATOR LABORATORY UNITED STATES DEPARTMENT OF ENERGY-NSC			
SSC 50mm DIPOLE COLD MASS COLLAR LAMINATION W/O SHIMS FOR VERTICALLY SPLIT YOKE			
SCALE 2 : 1 AND NOTED	FILED	DRAWING NUMBER	
		0102-ME-292059	C
CREATED WITH I-DEAS 5.0		USER NAME: NancyB	

REV.	DESCRIPTION	DATE	BY
A	OUTER RADIUS WAS 08.07/2.000 IS NOW 07.83/2.070 WITH NEW OFFSETS AND NEW RADIUS CENTER LOCATIONS. SEE DETAIL D FOR THESE NEW OFFSETS. SEE DETAIL F FOR NEW OUTER RADIUS DIMENSION LOCATIONS. 2X .00/.50/.250 HOLE .35/.250 THRU HOLE. .00/.50/.250 HOLE LOCATION HAS CHANGED. 48.38/1.000 WAS 63.87/2.121. 18.05/1.750 WAS 22.23/1.875 AND 36.10/1.500 WAS 44.78/1.750. SHOULDER DIM. OF 21.01-20.06/.827-.825 AND 21.29-21.21/.837-.835 WERE 21.09-21.07/.8300-.8296 AND 21.25-21.23/.8345-.8340 RESPECTIVELY. NOTE 8 WAS ADDED. CUTTER 0011 POLE FACES WAS CHANGED BY .008. THE FOLLOWING DIM. HAVE CHANGED. 08.50/2.687 WAS 08.33/2.680. 48.01/1.890 WAS 47.83/1.893. 37.38/1.471 WAS 37.47/1.475. 28.18/1.148 WAS 28.26/1.183. 0.88/.363 WAS 10.13/.368. 74.47/2.932 WAS 74.30/2.925. 84.10/2.528 WAS 84.01/2.520.	7/2/99	RD
B	REVISED RADI1 TO IMPROVE DIE WEAR: INCREASED NOTCH FOR STRAIN GAGE WIRES.	1/17/01	RD
C	1.878 WAS 1.875; (1.878) WAS (1.875); 3.758 WAS 3.750. REMOVED PART NO. STAMP.	3/08/01	RD

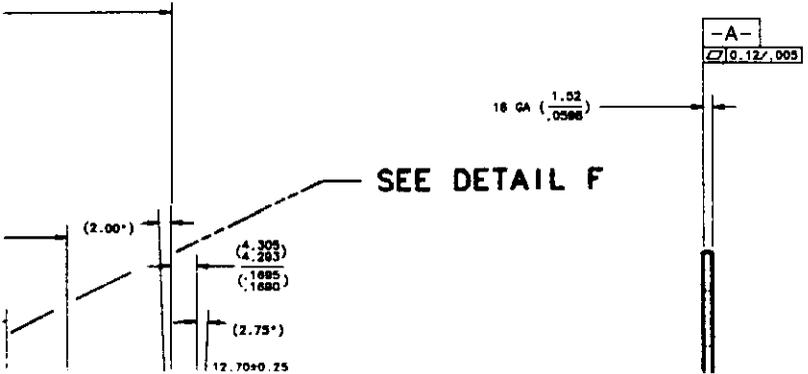
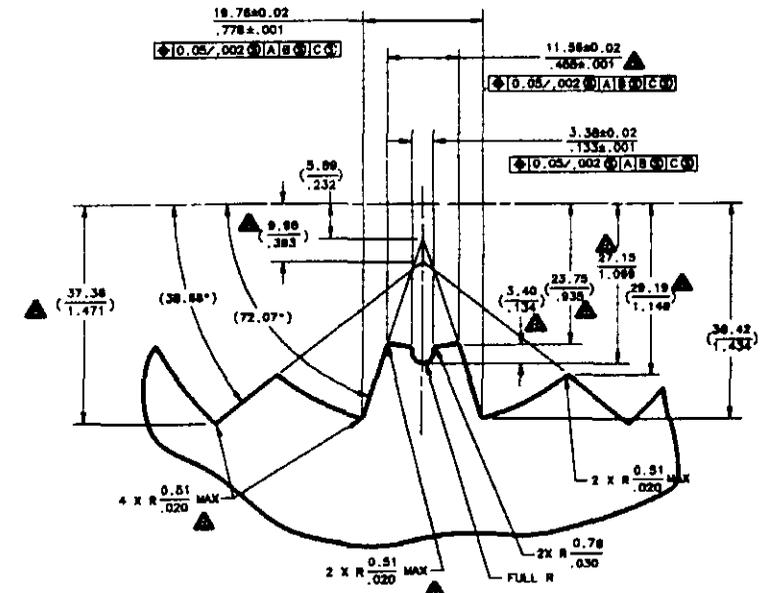
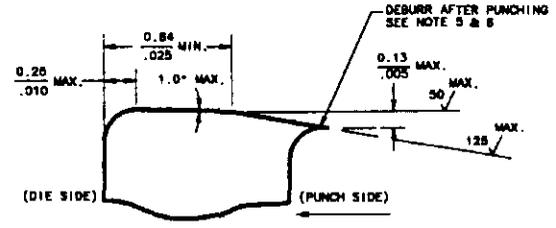
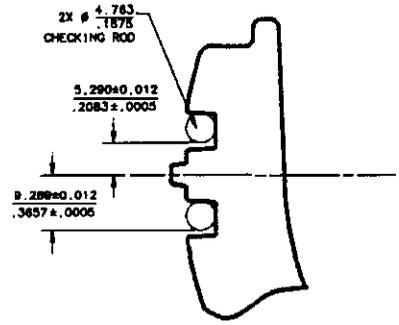
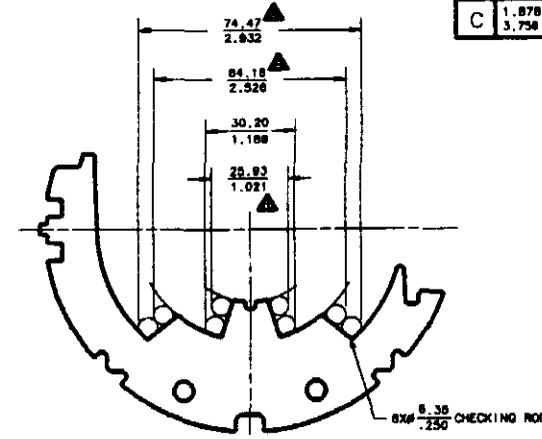
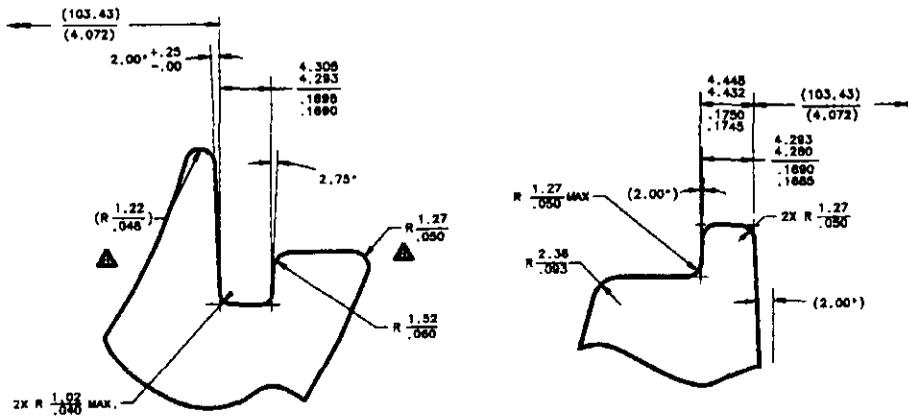
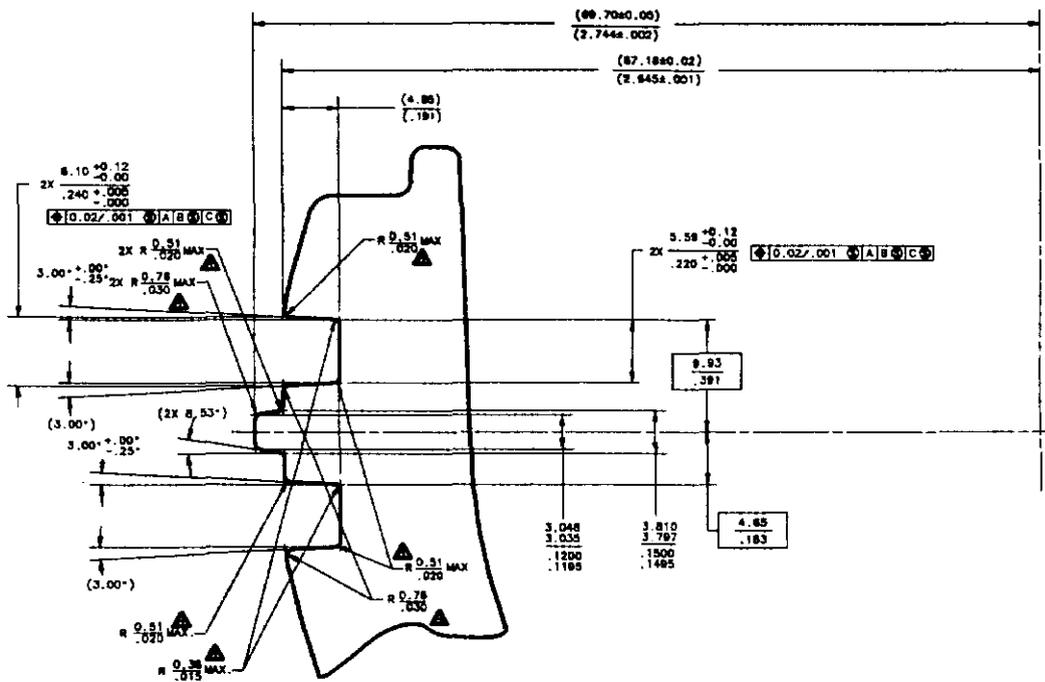


Figure 5c
24.



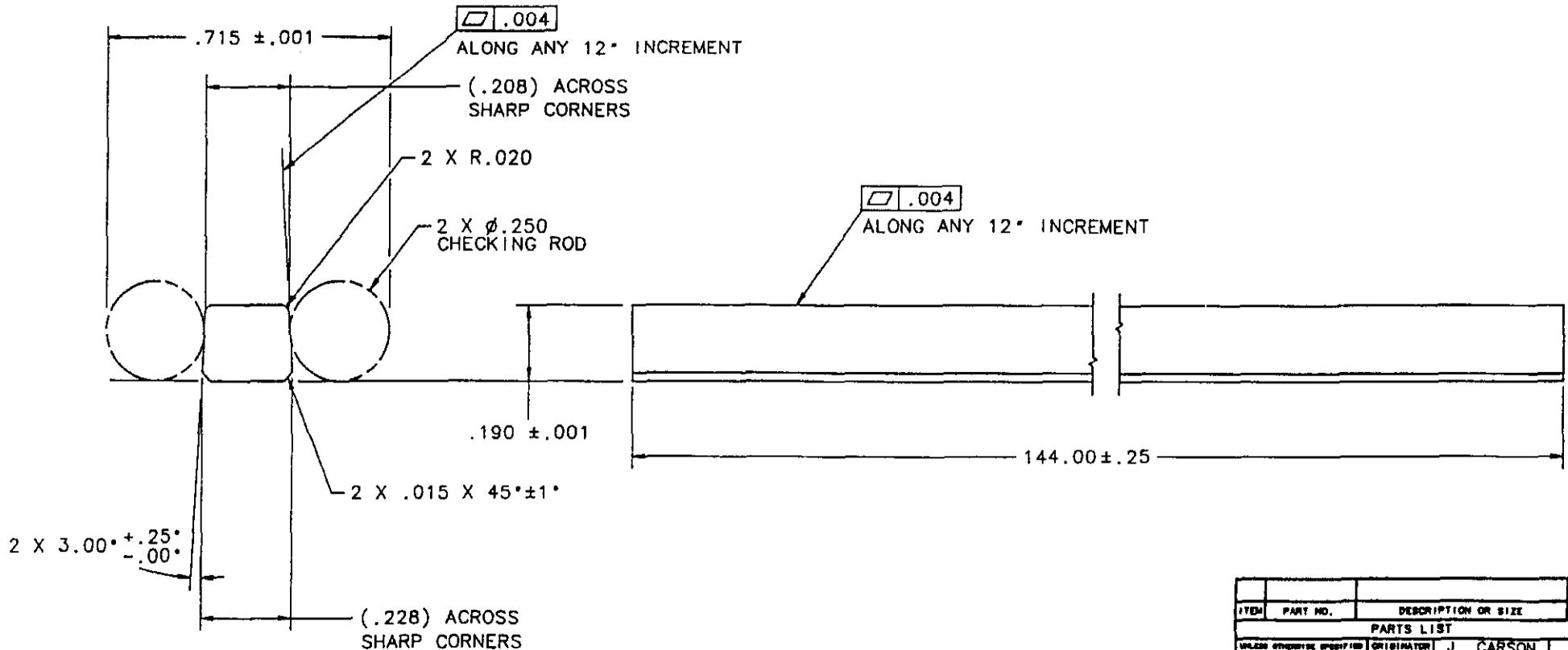
DETAIL A

SCALE 4 : 1

DIMENSIONS ARE TO INTERSECTION AS SHOWN

Figure 5d

REV.	DESCRIPTION	APPD.	DATE
B	REVISED MATERIAL; ADDED NOTE 1.	HWB	11/27/82



NOTES:

1. MATERIAL: PHOSPHOR BRONZE, 5x GRADE A, FULL HARD, ASTM B139 ALLOY 3/8 DIA. ROUND.
2. THIS PART IS INTERCHANGEABLE WITH BNL PART NO. 22-529.05-2 TAPERED KEY- STANDARD.

ACTUAL SIZE

ITEM	PART NO.	DESCRIPTION OR SIZE	QTY.
PARTS LIST			
UNLESS OTHERWISE SPECIFIED	ORIGINATOR	J. CARSON	
.XX	XX	DRW	J. CARSON 7-28-81
1.02	1.008	NA	C. Bossert 11-27-82
1. CHECK ALL SHARP EDGES FOR RADIUS.	APPROVED	R. Bossert	11-27-82
2. DO NOT SCALE DRAWING.	USED ON	0102-MB-217819	
3. DIMENSIONS UNLESS SPECIFIED ARE IN INCHES.	MATERIAL	SEE NOTE 1	
4. UNLESS ALL DIMEN. SURFACES ARE FINISHED.			
FERMI NATIONAL ACCELERATOR LABORATORY UNITED STATES DEPARTMENT OF ENERGY			
SSC MAGNET, DIPOLE C358D CROSS SECTION TAPERED KEY			
SCALE	FILED	WORKING DRAWING	REV.
4:1		0102-MB-217851	B
CREATED WITH I-DEAS 4.1 USER NAME: NAW/YN			

Figure 6

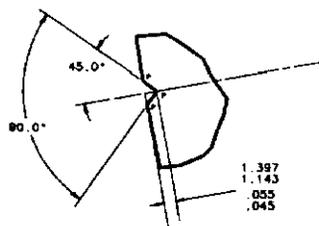
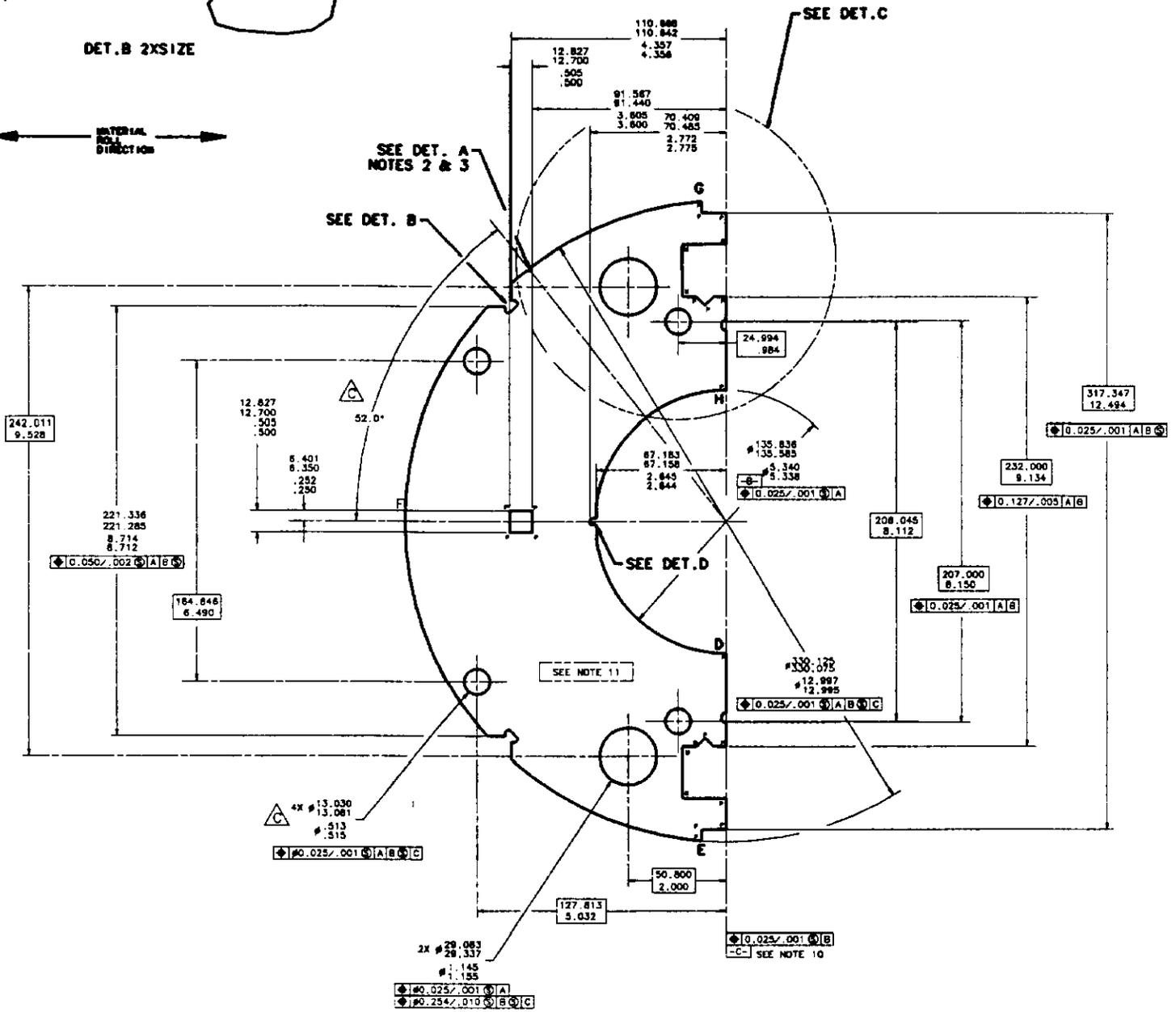
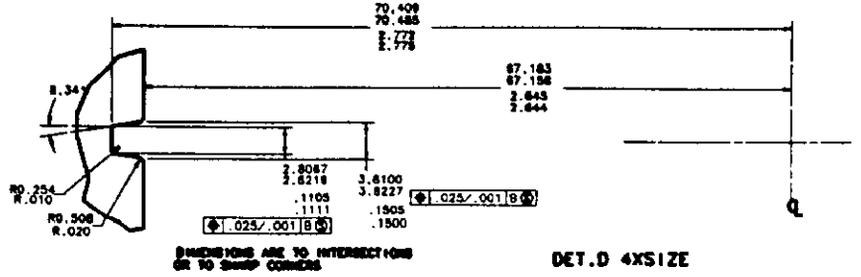
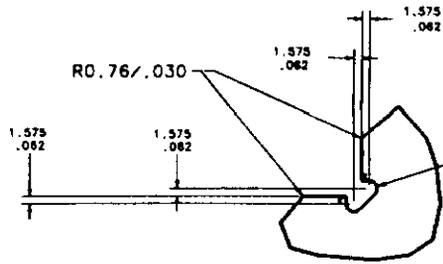
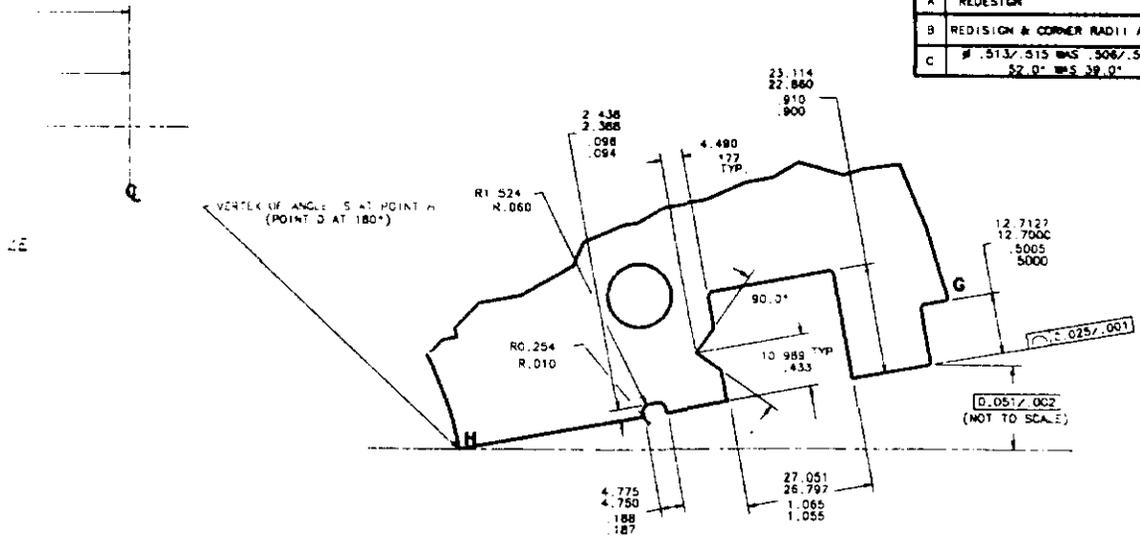
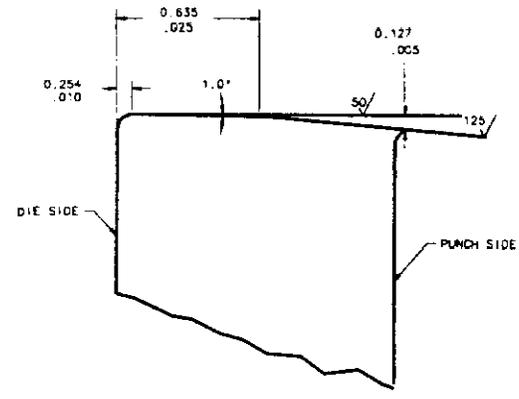
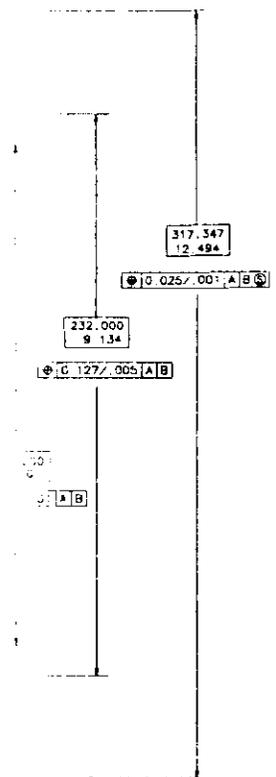


Figure 7a

REV.	DESCRIPTION	DATE	BY
A	REDESIGN	8/26/92	RW
B	REDESIGN & CORNER RADIUS ADDED	9/12/92	RW
C	Ø .513/.515 MAX .506/.508 52.0° ±.39.0°	2/6/93	RW



DET C 2XSIZE - SHOWN OUT OF POSITION
TYP. 2 PL. AT 180°



ENLARGED VIEW OF MAXIMUM MATERIAL
CONDITIONS FROM DIE OPERATIONS

CORNER RAD. DATA	
DESIGNATION	RADIUS
K	0.05/-.02 MAX
P	0.76/-.03 MAX
M	1.02/-.04 MAX

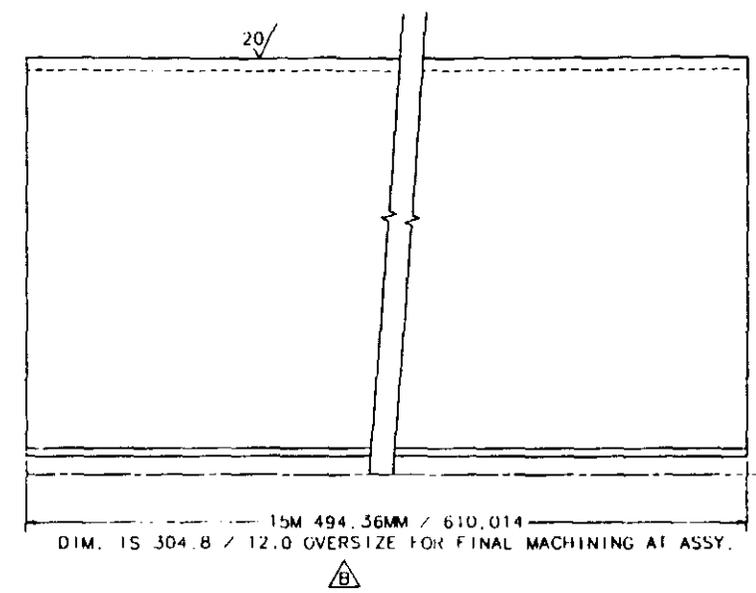
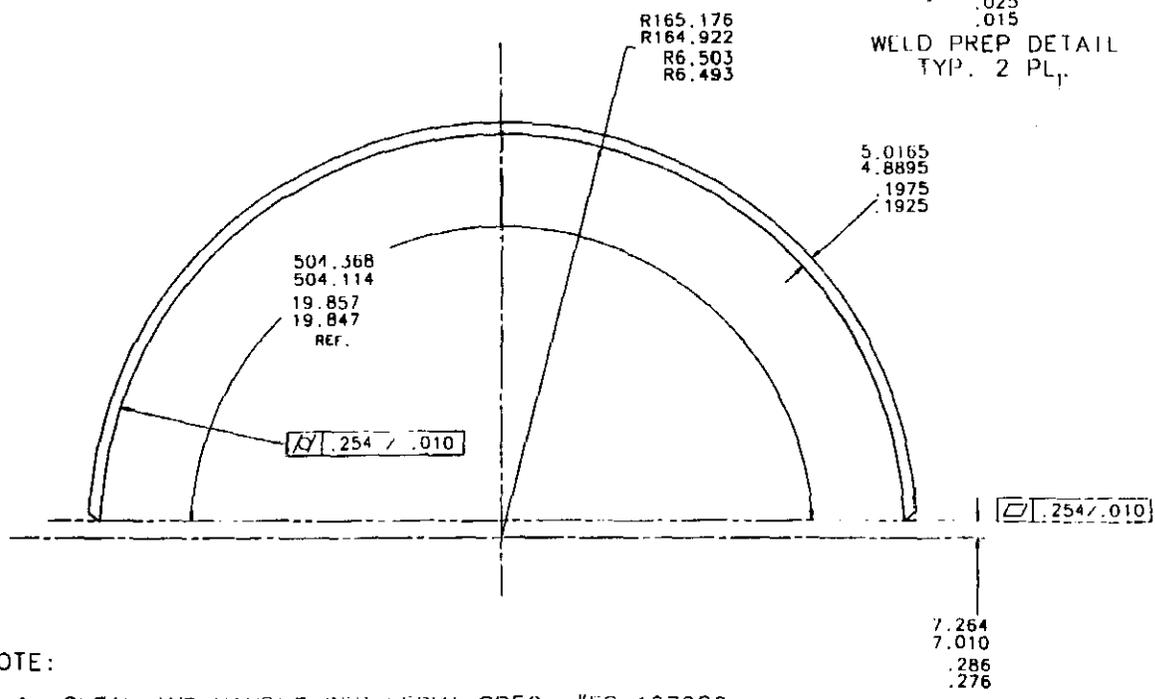
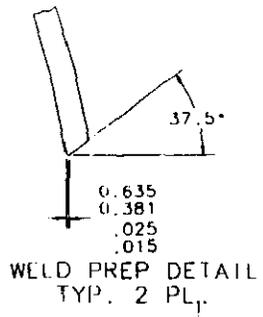
18 GA.
(1.519)
(.0598)
Ø 0.51/-.020
-A-

Figure 7b

- NOTES
- MATERIAL: EXTRA LOW CARBON MAGNET STEEL AS PER SPEC NO. SSC-MAG-M-4341
 - THIS NOTE TO BE INCORPORATED INTO ALL LAMINATIONS
 - ALL LAMINATIONS TO BE DIE PUNCHED WITH THE MAXIMUM MATERIAL THICKNESS COINCIDENTAL WITH THE EDGE DEFINED BY POINTS F, H, & G
 - ALL DIMENSIONS WILL BE MEASURED AND INSPECTED TO HIGHEST POINT ON EDGE PROFILE
 - USE WATER SOLUBLE STAMPING LUBRICANT ("ECK" DRAWING COMPOUND OR EQUIVALENT).
 - WT. PER LAMINATION = 83 LBS APPROX.
 - THIS YOKE LAMINATION IS MADE TO BE USED WITH ELLIPTICAL COLLAR LAMINATION. DWG. NO. 0102-ME-292059
 - ALL DIMENSIONS ARE SYMMETRICAL ABOUT CENTERLINE EXCEPT AS NOTED.
 - UNLESS OTHERWISE SPECIFIED, ALL TOLERANCES ARE ±.13MM / .005"
 - DATUM C IS DEFINED AS A LINE WHICH INTERSECTS THE THEORETICAL SQUARE CORNERS AT POINTS H & D.
 - STAMP OR DD IN "ME-292123" ON PART WITH NO UPSET OR INDENTATION - CHARACTER HEIGHT = .125"

ITEM	PART NO.	DESCRIPTION OR SIZE	QTY.
PARTS LIST			
ANALYSIS OTHERWISE SPECIFIED BY:			
1. ALL DIMENSIONS ARE TO BE MEASURED TO THE CENTERLINE UNLESS OTHERWISE SPECIFIED	DESIGNATOR	J. STRAIT	
2. DIMENSIONS BASED UPON THE THEORETICAL SURFACE UNLESS OTHERWISE SPECIFIED	DRAWN	ROGER ZIANK	8/26/92
3. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE TO BE MEASURED TO THE CENTERLINE UNLESS OTHERWISE SPECIFIED	CHECKED	H. BORDON	
4. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE TO BE MEASURED TO THE CENTERLINE UNLESS OTHERWISE SPECIFIED	APPROVED	R. BOSSERT	
5. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE TO BE MEASURED TO THE CENTERLINE UNLESS OTHERWISE SPECIFIED	DATE		
6. UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE TO BE MEASURED TO THE CENTERLINE UNLESS OTHERWISE SPECIFIED	MATERIAL	AS NOTED	
FERMI NATIONAL ACCELERATOR LABORATORY UNITED STATES DEPARTMENT OF ENERGY SSC			
SSC (50mm) SHORT/LONG COLD MASS W6733 CROSS SECTION VERTICAL SPLIT YOKE LAMINATION			
SCALE	TITLES	DATE	REV.
1:1		0102-ME-292123	C
CREATED WITH 1-DFAS 4.1		USER NAME: WEGFORTH	

A	NOTE 1 ADDED	NO	10/12
H	610-014 WAS 610-75	NO	1/24/68



NOTE:

1. CLEAN AND HANDLE PER FERMI SPEC. #ES-107222
2. THE INSPECTION OF THE SKINS WILL BE DONE IN A CONSTRAINED CONDITION. THE DIMENSIONS ON THIS DRAWING PERTAIN TO THAT CONSTRAINED CONDITION AND WILL NOT BE INSPECTED IN ANY OTHER MANNER. WHEN REFERRING TO THE CONSTRAINED CONDITION IT IS DEFINED BY THE FOLLOWING: THE SKIN WILL BE CONSTRAINED IN THE SAME CONDITION THAT IT WILL HAVE WHEN CLAMPED TO THE 1 PHASE IRON, THIS CONSTRAINING WILL IN NO WAY FORCE THE SKIN INTO A CONFIGURATION OTHER THAN IT'S OWN. IN OTHER WORDS IT IS NOT ACCEPTABLE TO FORCE OR INDUCE A TWIST TO ACHIEVE THE ABOVE DIMENSIONS.

Figure 8

ITEM	PART NO.	DESCRIPTION OR SIZE
PARTS LIST		
PROCESS WITH BASIC IDENTIFICATION		
1. ALL DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN MILLIMETERS	ORIGINATOR	J. CARSON
2. DIMENSIONS TO BE CHECKED	DATE	8/10/68
3. DIMENSIONS TO BE CHECKED	CHECKED	
4. DIMENSIONS TO BE CHECKED	APPROVED	Subj. Des. P. 117
5. DIMENSIONS TO BE CHECKED	USED ON	
6. DIMENSIONS TO BE CHECKED	MATERIAL	304LN S.S.
FERMI NATIONAL ACCELERATOR LABORATORY UNITED STATES DEPARTMENT OF ENERGY B-5C		
SSC 50MM LONG COLD MASS FINAL ASSEMBLY SKIN		
SCALE	FILE NO.	PROCESS NUMBER
1-1		0102-MD-292156

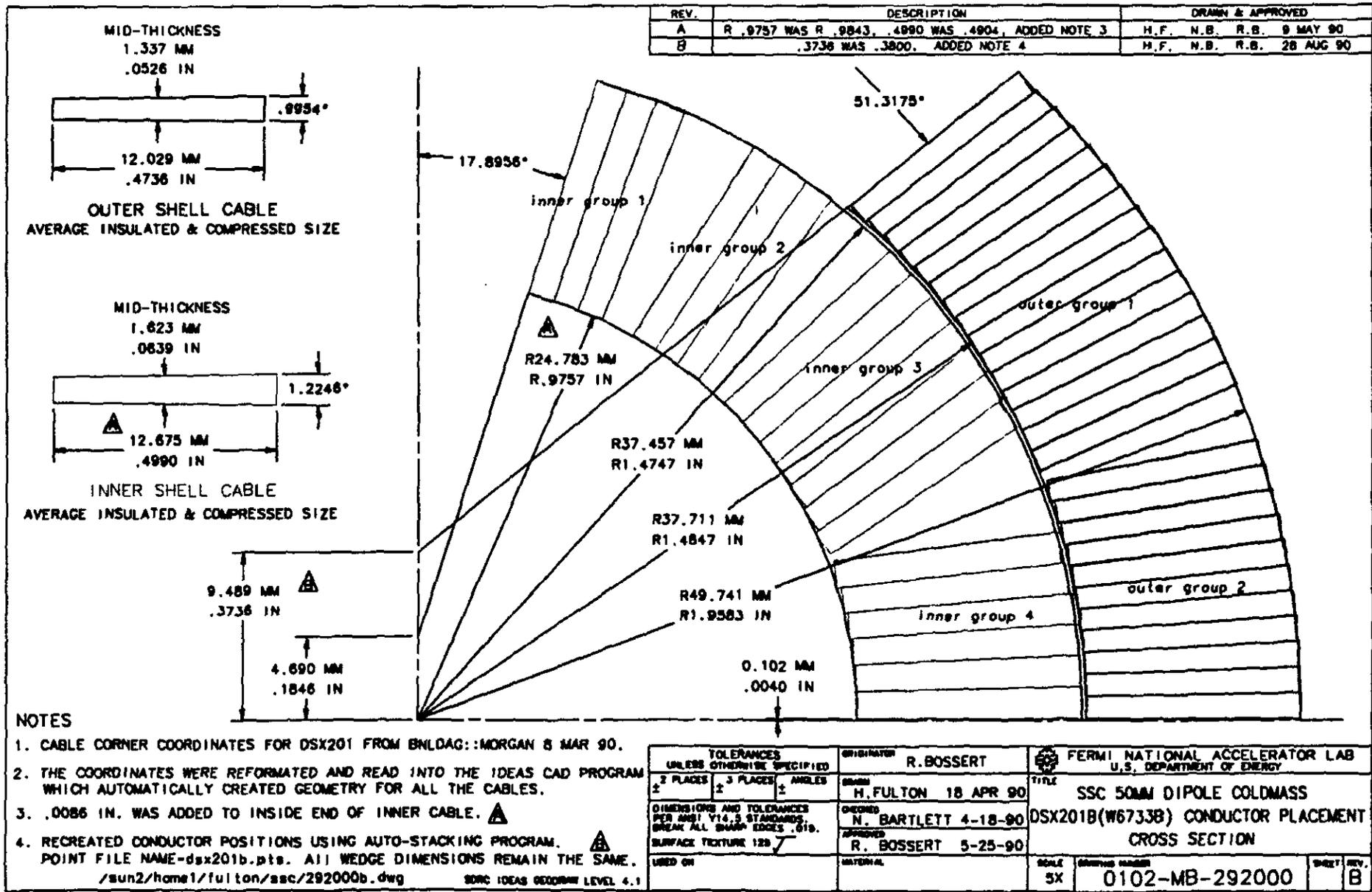
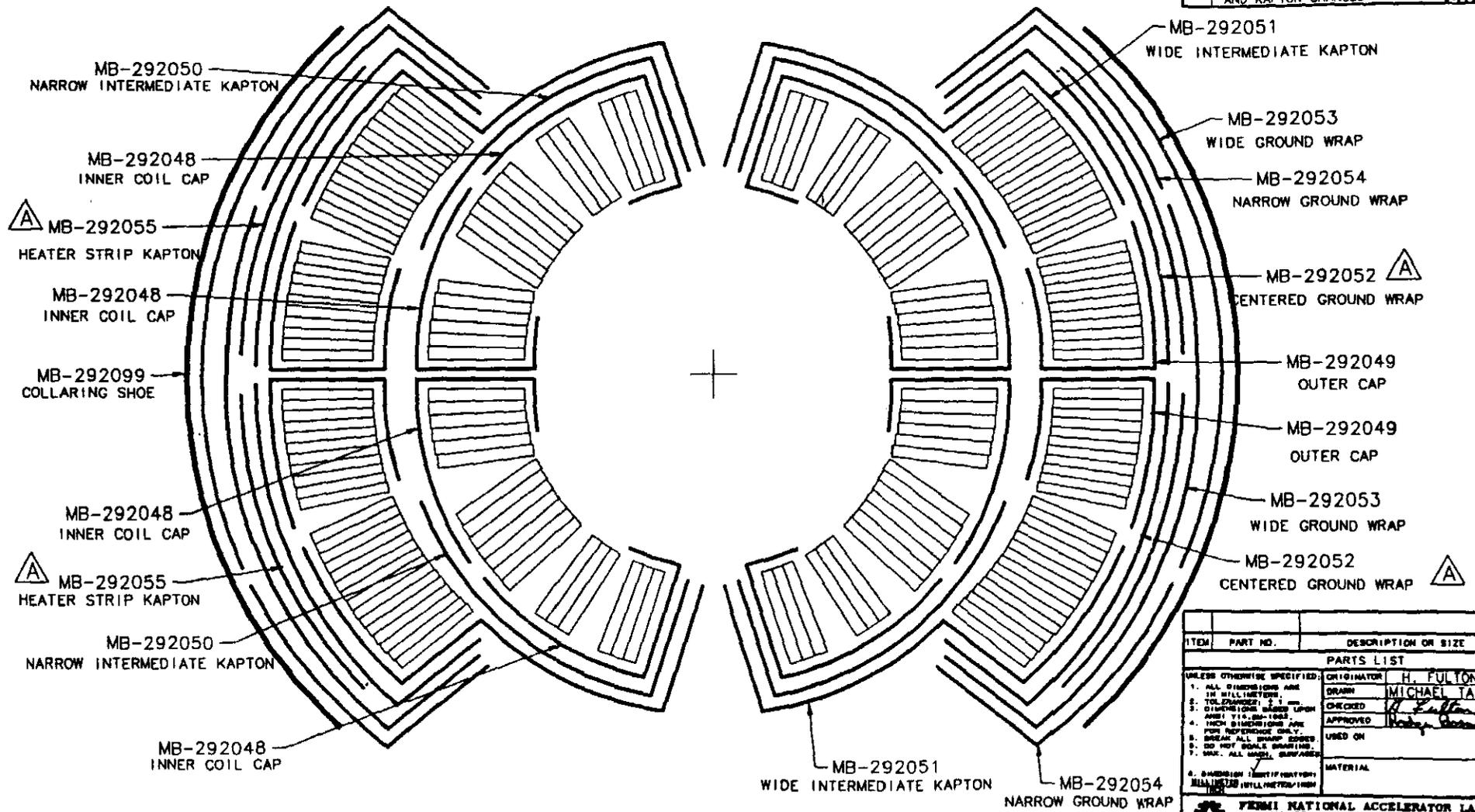


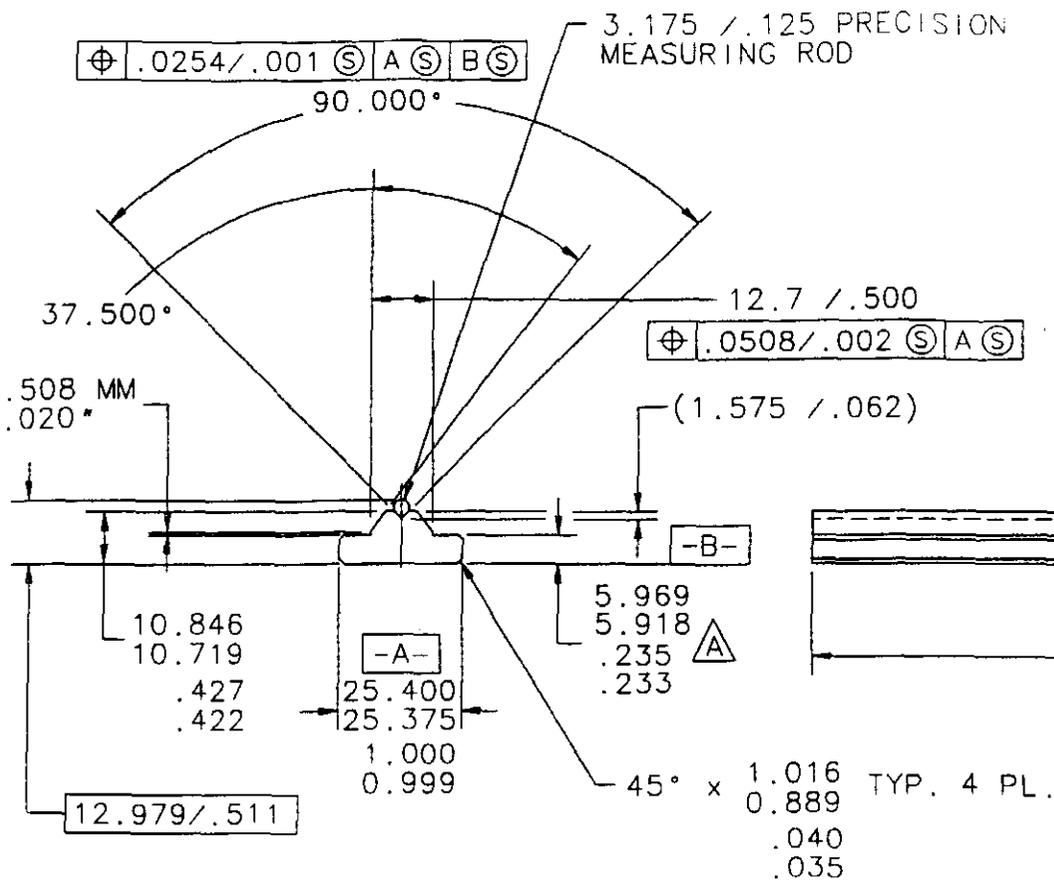
Figure 9
30.

REV.	DESCRIPTION	DATE	BY
A	POSITION OF HEATER STRIP AND KAPTON CHANGED	8-28-9	MATE

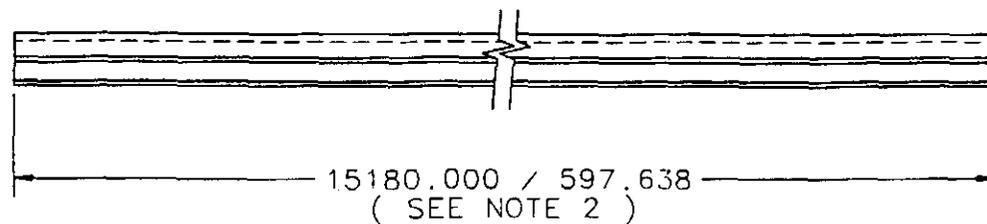


ITEM	PART NO.	DESCRIPTION OR SIZE	QTY
PARTS LIST			
UNLESS OTHERWISE SPECIFIED:		ORIGINATOR	H. FULTON
1. ALL DIMENSIONS ARE	IN MILLIMETERS	DRAWN	MICHAEL TATE 5-18-
2. TOLERANCES UNLESS NOTED	ARE:	CHECKED	H. Fulton
3. DIMENSIONS IN PARENTHESIS	ARE FOR INFORMATION ONLY	APPROVED	Hobby, Brown, BSC
4. DIMENSIONS IN SQUARE BRACKETS	ARE FOR INFORMATION ONLY	USED ON	
5. BREAK ALL SHARP EDGES	TO R0.5 UNLESS NOTED	MATERIAL	
6. DO NOT SCALE DRAWINGS			
7. MAKE ALL MESH SURFACES			
8. DIMENSIONS IN PARENTHESIS	ARE FOR INFORMATION ONLY		
FERMILAB NATIONAL ACCELERATOR LABORATORY UNITED STATES DEPARTMENT OF ENERGY BSC			
SSC 50MM DSX201A DIPOLE COLDMASS COIL PACKAGING INSULATION ASSY ASSEMBLY			
SCALE	2X	REVISED NUMBER	0102-MB-292047
CREATED WITH I-DEAS 4.1		USER NAME: MATE	

Figure 10



FLAT WITHIN .127 / .005 PER FOOT
 TWIST NOT TO EXCEED .127 / .005
 PER FOOT.



REV	DATE	BY	APP'D
A		NOTE 3 ADDED	RW 10/22/88

NOTE:

1. ALL CORNER RADII TO BE .254 / .381 - .010 / .015 UNLESS OTHERWISE SPECIFIED.
2. OPTIONAL - 3657.6 MM / 12'-0" LG'S. TO MAKE UP O.A.LG.
3. CLEAN AND HANDLE PER FERMI SPEC. #ES-107222

Figure 12

ITEM	PART NO.	DESCRIPTION OR SIZE	QT
PARTS LIST			
UNLESS OTHERWISE SPECIFIED:		ORIGINATOR	J. CARSON
1. ALL DIMENSIONS ARE	IN MILLIMETERS	DRAWN	R. WEGFORTH 10/22/88
2. TOLERANCES: ± 0.1 MM		CHECKED	<i>[Signature]</i> 10/22/88
3. DIMENSIONS BASED UPON	ANSI Y14.2M-1983	APPROVED	<i>[Signature]</i> 10/22/88
4. 1/8" DIMENSIONS ARE	FOR REFERENCE ONLY.	USED ON	
5. BREAK ALL SHARP CORNERS.		MATERIAL	304LN S.S.
6. DIMENSION IDENTIFICATION:	MILLIMETER/MILLIMETER/INCH		
FERMI NATIONAL ACCELERATOR LABORATORY UNITED STATES DEPARTMENT OF ENERGY SSC			
SSC 50MM LONG COLD MASS FINAL ASSEMBLY ALIGNMENT KEY			
SCALE	FILMS	ORDER NUMBER	WT
1-1		0102-MB-292155	A
CREATED WITH I-DEAS 4.1		USER NAME	WEGFORTH