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Design and Fabrication of Tuning Shims for Magnetic Field Optimization

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1. Introduction

A proposal for HGQ experiments involving magnetic shims for correction of non-allowed low-order harmonics has been put forward by Sabbi [1]. The proposed correction strategy attempts to correct the observed sextupole and octupole errors at nominal current by exploiting the symmetry in the harmonics generated by different tuning shims. It has been shown by Sabbi [2] that "to maintain the accuracy of the sextupole correction within $\pm\sigma/3$, the required position accuracy is 0.25 mm (0.010"). This means that the mechanical tolerances must be such that the lamination packs are placed within ±0.25 mm of their desired positions." This places tight tolerances on the assembled thickness of the tuning shims, which should also fit precisely in the cavity within an accuracy of ± 0.010". This note describes briefly the design constraints involved, the chosen design and the fabrication methodology.

2. Design and Fabrication

Fig. 1 shows a schematic of the cross-section of a High Gradient Quadrupole magnet, showing the eight cavities where the tuning shims are supposed to go. It should be noted that the tuning shim cavities are defined by the yoke and collar lamination surfaces. Based on the measured low-order cold harmonics of HGQ01 ($b_3<0.5$, $b_4<0.5$, $a_3<0.5$, $a_4 = +2.0$), it was proposed by Sabbi to use a scheme for correction of a_4 with predicted zero change on the others. It should be noted that b_3, a_3, b_4, and a_4 are the only four harmonics which can be corrected with the tuning shims. The proposed correction scheme involved two types of shims: one with 4.1 mm (0.161") of iron and the other with 15.9 mm (0.626") of iron. The rest of the cavity needs to be tightly filled with a non-magnetic material. It should be noted that during ramping up and ramping down of HGQ01 and HGQ02, snapshot events were captured by the quench detection system at thresholds lower than those used to trigger real quenches [3]. These snapshot events were attributed

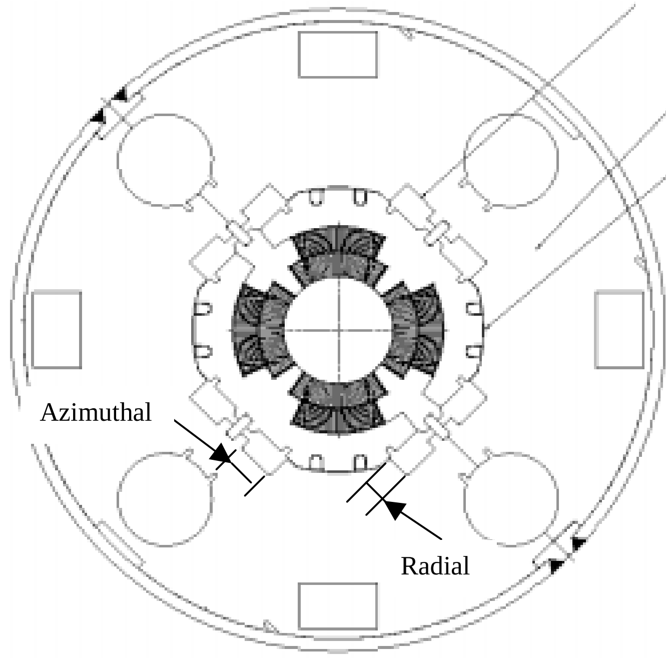

Fig. 1 A cross-sectional view of the High Gradient Quadrupole magnet. The eight tuning shim cavities are defined by the yoke and collar laminations.

to the moving of the original tuning shims within the cavity. The nominal design of the original tuning shims was based on a radial dimension of 0.613” ± .005”, whereas the azimuthal dimension was 0.384” ± .005” for the magnetic shim (Drawing Number 5520-MB-344767) made of 1020 H.R.S. and 0.564” ± .005”for the non-magnetic shim (Drawing Number 5520-MB-344766) made of C360 Brass. The length of these original shims was 56.95”. The existing radial and azimuthal dimensions of the shims provided sufficient clearance to slide the shims inside the tuning shim cavity along the length of the magnet. However, the clearance was large enough to cause a movement of the shims during ramp up and ramp down. Therefore, it was necessary to adjust the shim size to provide as snug of a fit as possible while still having the clearance necessary to slide the shims along the entire length of the magnet. It should be noted that the idea of sliding the shims after magnet assembly was envisioned because that allowed for measurement of harmonics (warm and cold) after magnet assembly, coming up with a scheme to correct undesirable harmonics based on magnetic measurements, and then assembling different shim configurations to correct the undesirable harmonics. Therefore, it was decided to assemble the shims from some standard thickness shims (magnetic and non-magnetic), which would allow to change the azimuthal thickness of the assembled magnetic shim within the range of 0 to 20 mm.

Also, it was required that these assembled shims fit snugly in the cavity. Since the cavity size is determined by the dimensions of the yoke and collar laminations, a statistical analysis of the maximum and minimum cavity size was performed based on the inspection reports of the collar and yoke laminations. The azimuthal cavity size is determined by the yoke dimensions and was observed to be within 0.988” ± 0.002”.

Thus, the theoretical minimum azimuthal size for the cavity is 0.986” which implies that the theoretical total thickness of the assembled stack should be **0.986”** minus the clearance needed to slide the shims inside the cavity. However, buckling of the yoke laminations towards the end of the magnet has been observed which decreases the maximum azimuthal size of the shims which can be inserted into the magnet.

The radial size of the shims (which also determines the width of the shim material ordered) is determined by the collar and yoke laminations. It was observed that the relevant collar dimensions were within 3.201” +0.0003” and –0.0024” and yoke dimensions were within 3.8449” +0.0008” and –0.0012”. Thus, the cavity size was within 0.644” +0.0032” and –0.0015”, i.e., between 0.6425” and 0.6472”. Accounting for 0.005” radial deflection of the collar due to spring back gives minimum radial cavity size to be **0.6375”**.

To verify the theoretical numbers, a tooling was developed to measure the radial cavity (Fig. 2) and the azimuthal cavity (Fig. 3). The developed tooling allowed for changing the total thickness of the tooling by putting some shims in between to allow determination of the maximum thickness of the tooling that could be slided in the shim cavity. Based on these measurements, it was observed that the dimensions of the shim cavities varied for the 8 cavities: whereas a certain thickness tooling would go into certain cavities without any problem, it would get stuck in some other cavities. The maximum radial thickness that would go inside all 8 cavities for magnet HGQ01 was observed to be **0.628”**, whereas the maximum azimuthal thickness that would go inside all 8 cavities for HGQ01 was **0.975”**. However, note that tooling with azimuthal thickness of 0.975” would not go inside the cavities of HGQ03 due to more severe buckling of the end yoke laminations for this particular magnet. The maximum azimuthal size that would go inside magnet HGQ03 was observed to **be 0.9705”**.

Based on these measurements, it was decided to order shim material of width **0.623”** ± **0.005”** so that the maximum possible width of the shim material would still fit inside the cavity. Also note that the total azimuthal thickness of the assembled shim stack is within our control. It was decided to order 1010 full hard steel shims of thicknesses 0.078” and 0.004” and C260 half hard brass shims of thicknesses 0.080” and 0.004”. The shims were to be assembled using 828 V-40 epoxy at room temperature cure. A fixture was designed and fabricated (see Fig. 4 for the sketches and Fig. 5 for a photograph of the fixture) to assemble the tuning shims. The main requirement for the fixture was to provide a very uniform thickness of the assembled tuning shim stacks over its entire length. Two different sets of tuning shims of quantity four each were assembled. Whereas one set comprised of eight 0.078” thick iron laminations, the other stack was made of two 0.078” thick and one 0.004” thick iron laminations. Figures 6 and 7 provide the variation in thickness of the assembled tuning shims for the two different configurations. It is observed that except at the ends, the thickness of the assembled shims is very uniform over their entire length. Note that the increased thickness observed in the ends is due to some twist which was present in the laminations and could be eliminated if laminations with no twist are used. With this caveat, we would like to emphasize that the chosen assembly methodology and the designed fixture is capable of providing assembled shims of very precise total thickness. This has important implications in providing shims which can fit very precisely in the designed cavity.

An experimental study was conducted by P. Schlabach and J. DiMarco to compare the experimental change in the harmonics (due to the shims) to the theoretical predictions by G. Sabbi. It was observed that the experimental results provided a good agreement to the theoretical predictions. Another study was conducted to study the effect of the variability in the assembled shims of the same configuration on magnetic field change. It was concluded that no variability in the shims outside the range of measurement could be observed due to the inadequacy of the measurement system. However, finally it was decided not to use the tuning shims in the HGQ magnets due to the following major reasons (as provided by J. Kerby):

1. We are within the error table of the harmonics which can be affected by tuning shims (sextupole and octopole) in the current models, using the "nominal" shim (50% iron), and not attempting to shim these errors out. We believe, by controlling coil size, which we need for the remainder of the harmonics anyway, we can control these harmonics to within the desired range. Furthermore, in our current design the b6 seems to be the big issue, which we will need to evaluate further (but which shims do us no good on anyway).
2. In the HGQ05 design, with end cans over both ends of the magnet, the shims must be installed before yoke and skinning of the magnet, and are not available for modification beyond that without large reconstruction of the magnet. To do this, we need a good warm measurement (possible), and an understanding of the warm to cold correlation for these harmonics (also possible).

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ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
	HGQ	X6490	

SUBJECT	NAME	DATE	REVISION DATE
Tuning Shim Cavity Measurement Tool — A	Sunil Yadav	09/07/98	LRD

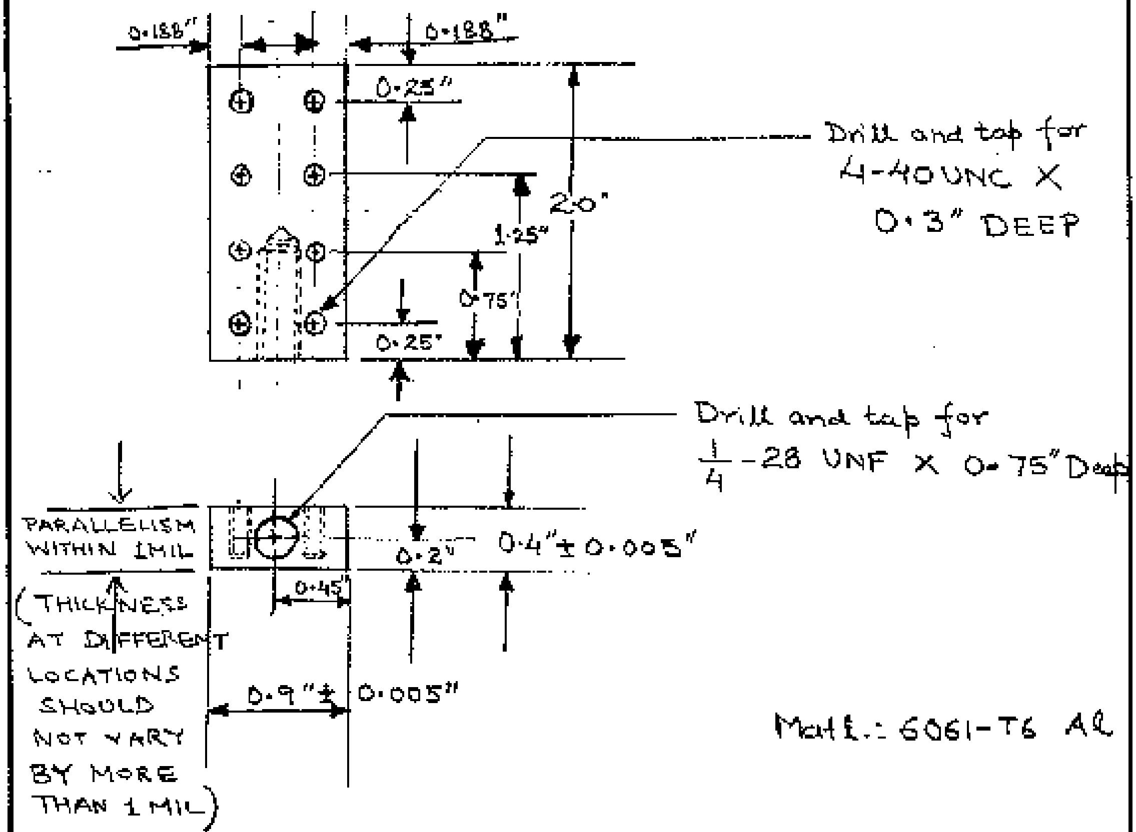

Fig.2 Tooling to measure radial cavity size.

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	HGQ	X 6490	

SUBJECT: Tuning Shim Cavity Measurement Tool - B

NAME: Sunil Yadav

DATE: 09/07/98

REVISION DATE: LRD

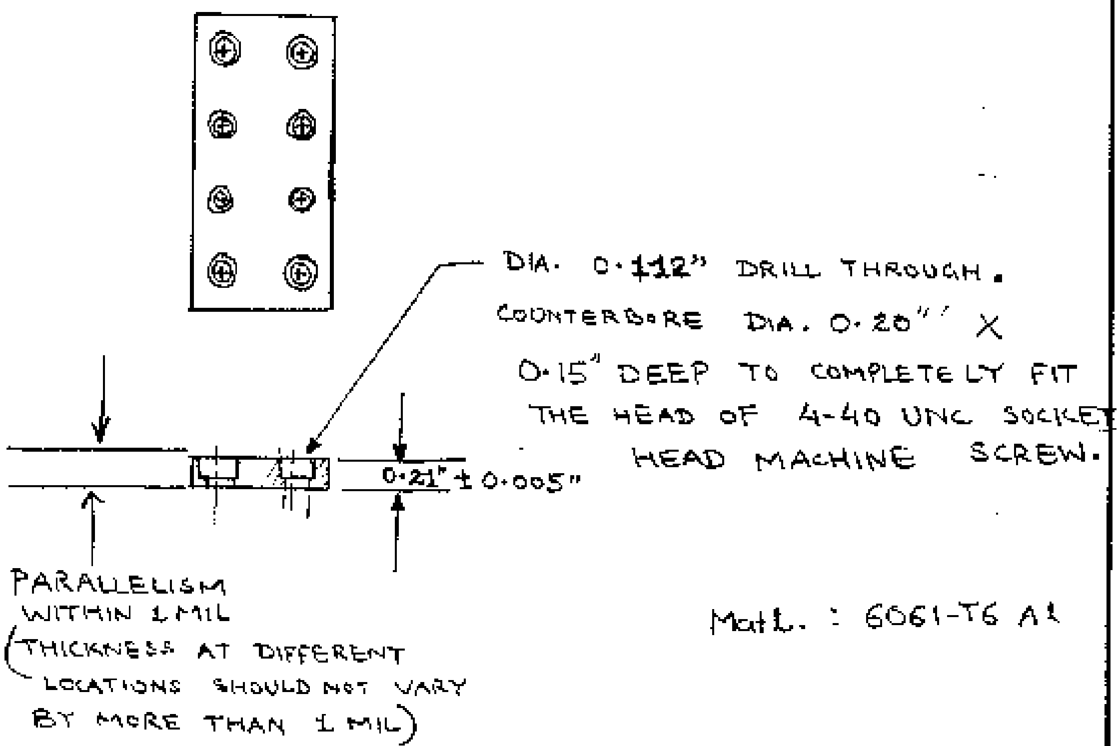

Fig. 2 Tooling to measure radial cavity size.

TUNING SHIM HORIZANTAL CAVITY MEASUREMENT TO

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		HGQ	X6490	

SUBJECT	NAME	
Parallelism within 1 mil.	SUNIL YADAV	
	DATE 10/29/98	REVISION DATE LRD.

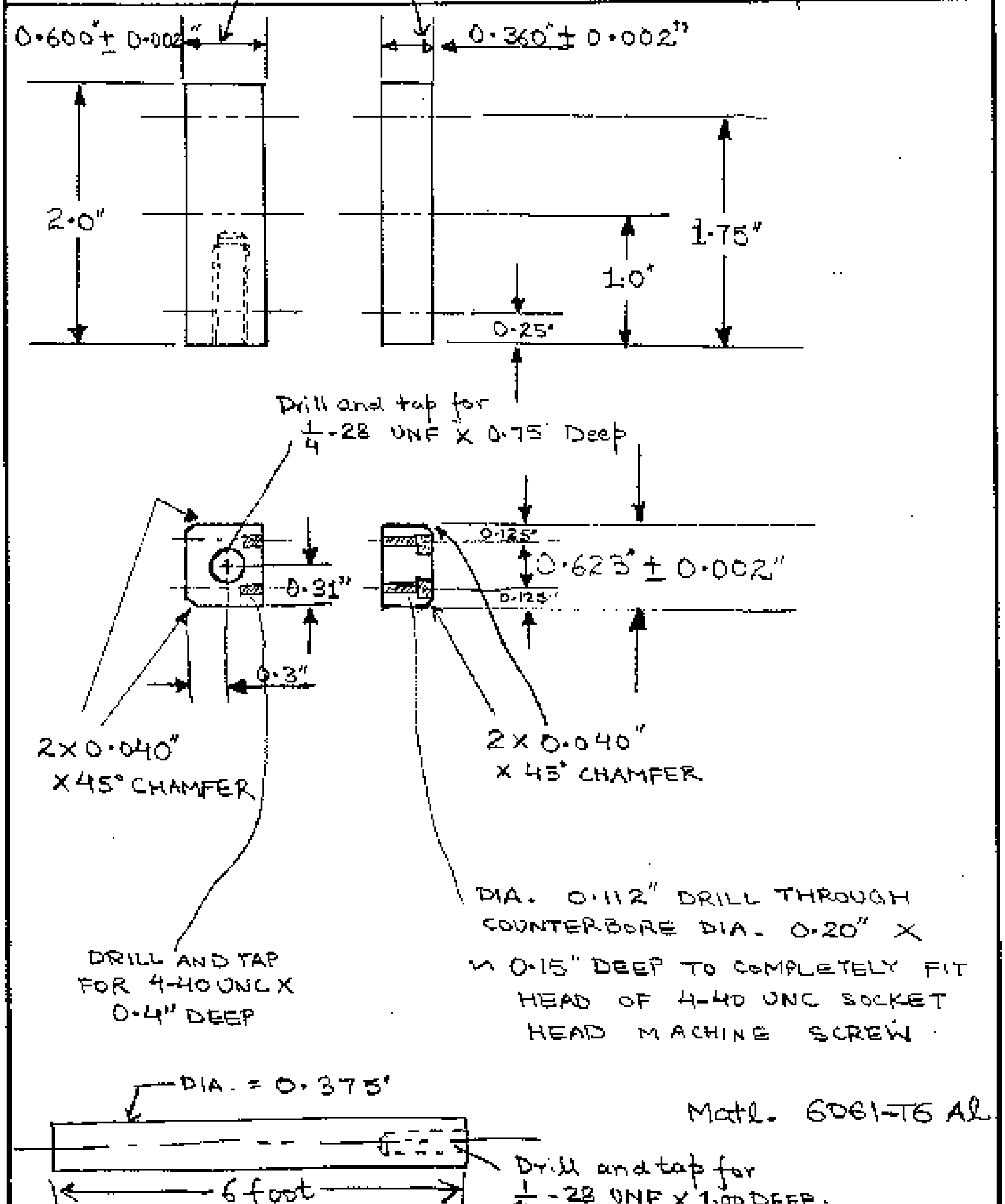
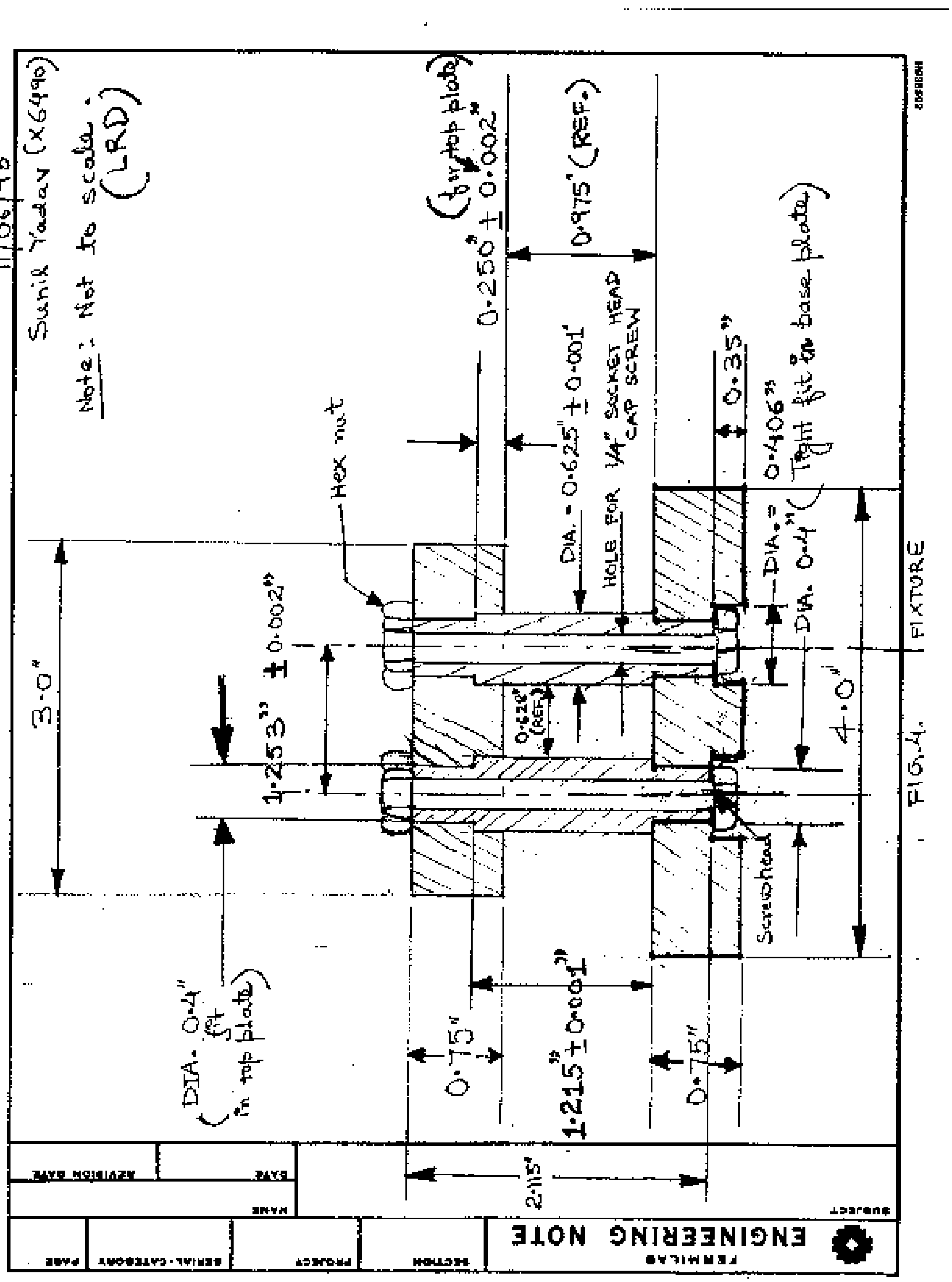


FIG-3. Tooling to measure azimuthal cavity size.


11/06/98
Sunil Yadav (X6490)
Note: Not to scale. (LRD)
Hex nut
Screwhead
FIG. 4. FIXTURE
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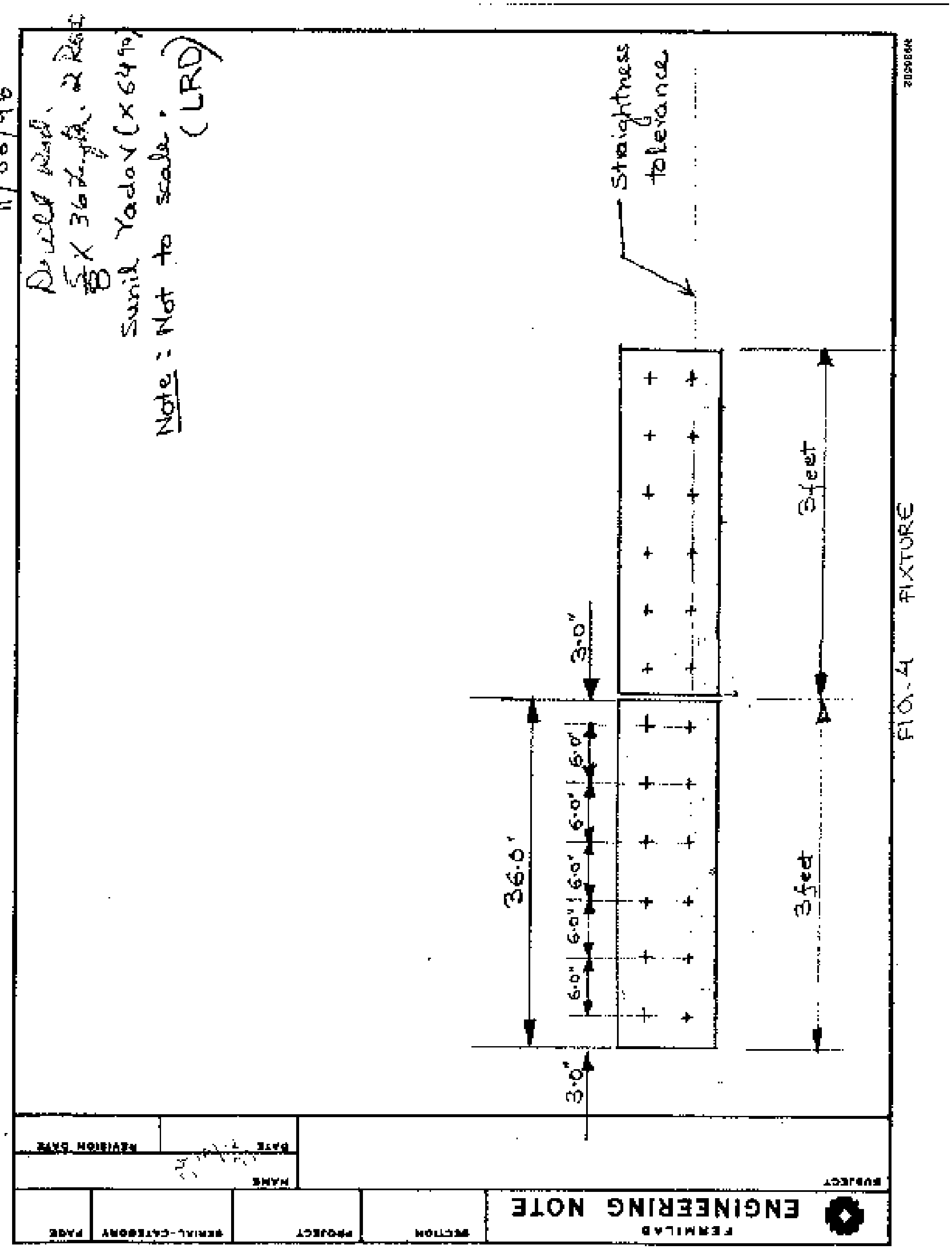


FIG. 4 FIXTURE

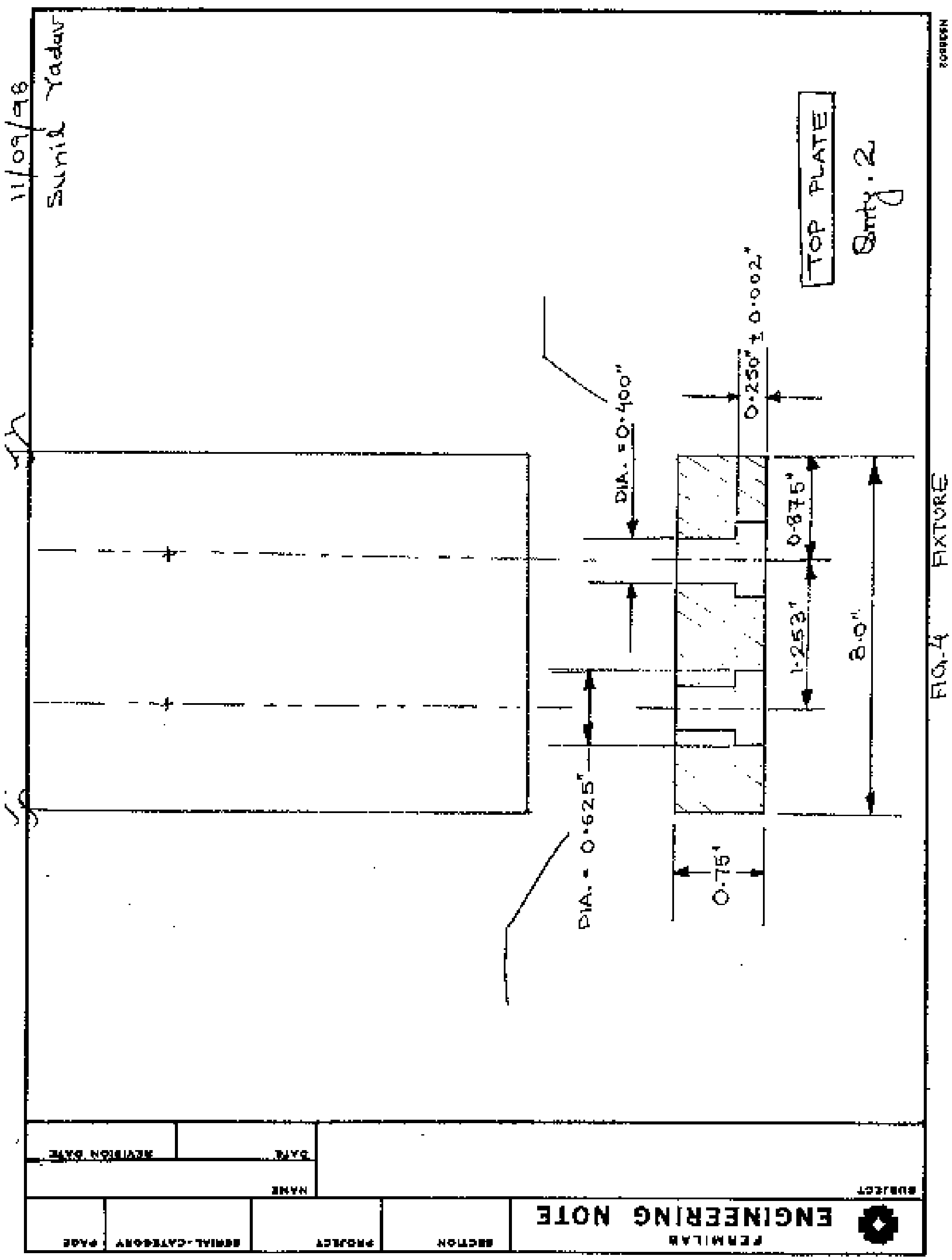
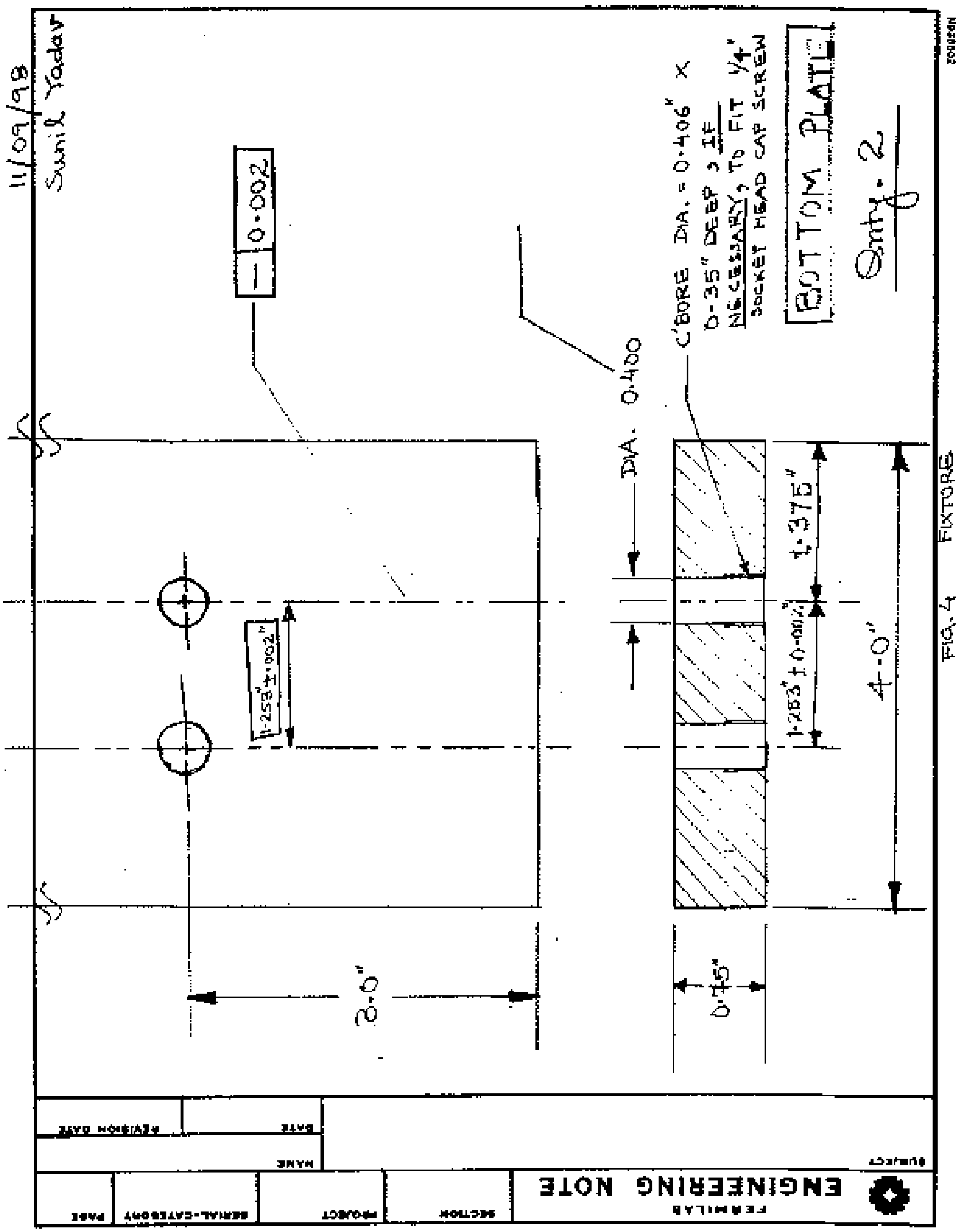


FIG. 4 FIXTURE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Sunil Yadav
0.002
DIA. 0.400
C'BORE DIA. = 0.406" X 0.35" DEEP, IF NECESSARY, TO FIT 1/4" SOCKET HEAD CAP SCREW
BOTTOM PLATE
Qnty. 2
1.375"
1.253" ± 0.002"
4-0"
3.0"
0.75"
FIG. 4 FIXTURE
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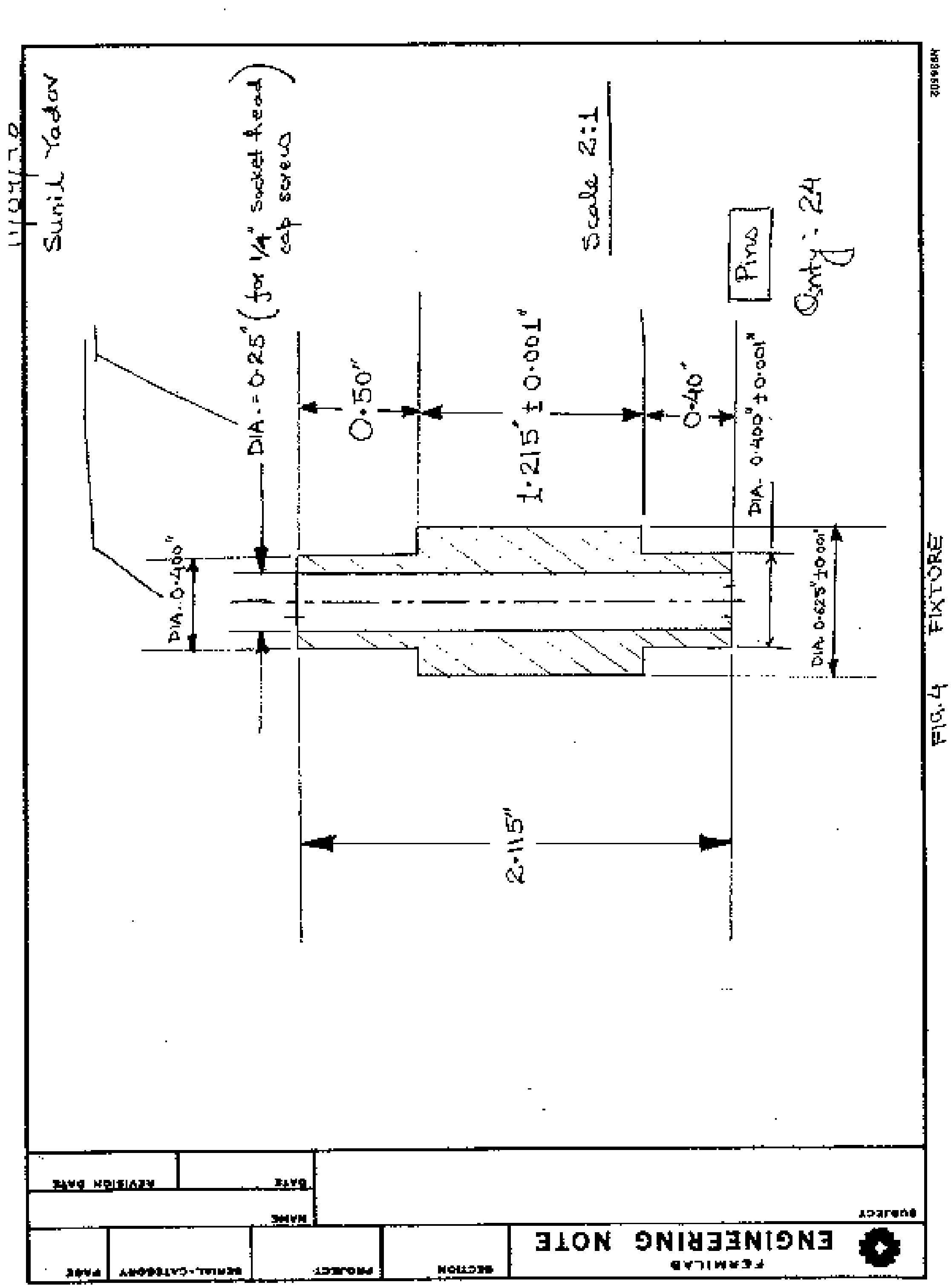

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DIA. = 0.25" (for 1/4" socket head cap screw)
0.50"
1.215" ± 0.001"
0.40"
Scale 2:1
Pins
Qnty: 24
DIA. 0.400" ± 0.001"
DIA. 0.400"
DIA. 0.625" ± 0.001"
2.115"
FIG. 4 FIXTORE
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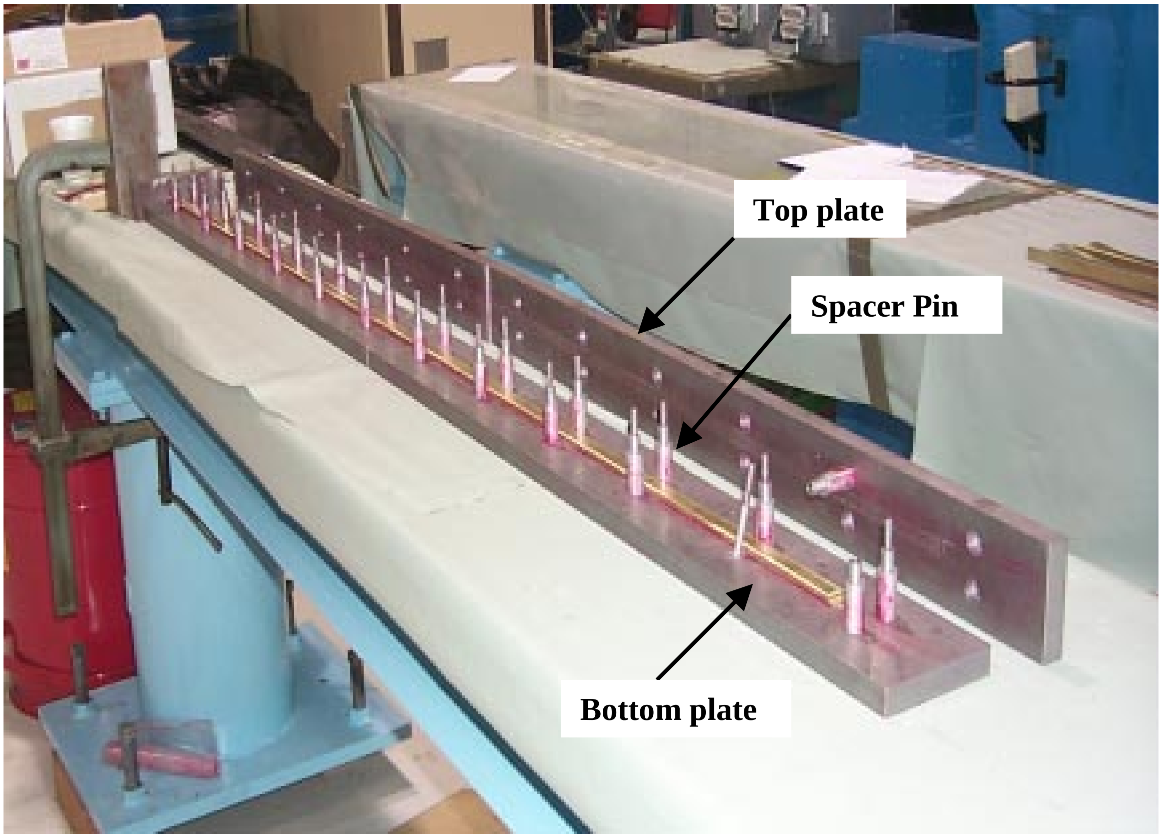

Fig. 5 A photograph of the assembly fixture used to assemble the tuning shims together. The top plate gets bolted down to the bottom plate while the spacer provides very precise control on the assembled thickness of the tuning shim stack.

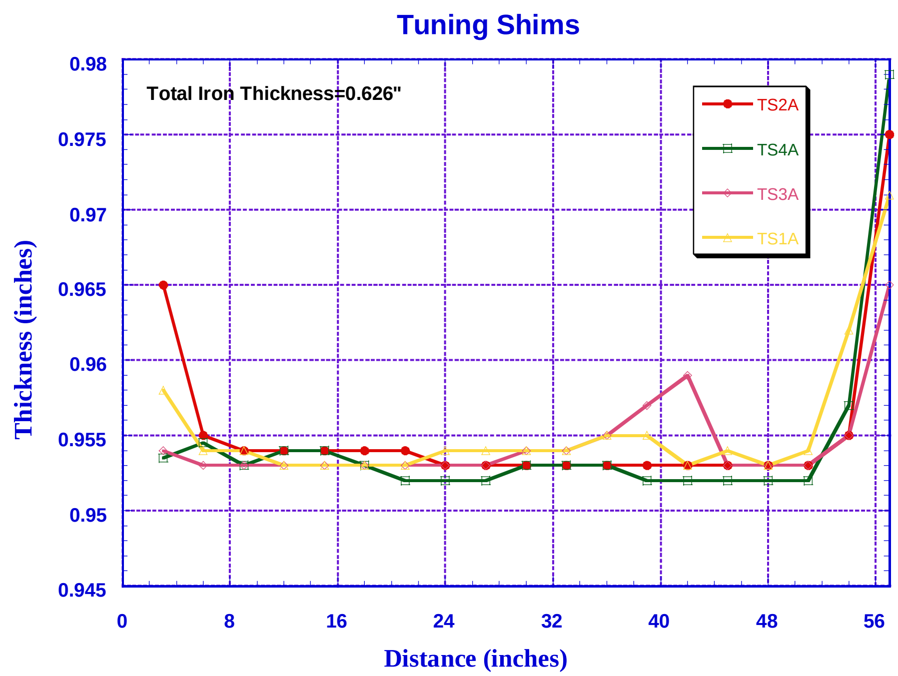

Fig. 6 The variation in thickness of the tuning shims along their length for the configuration with total iron thickness of 0.626”.

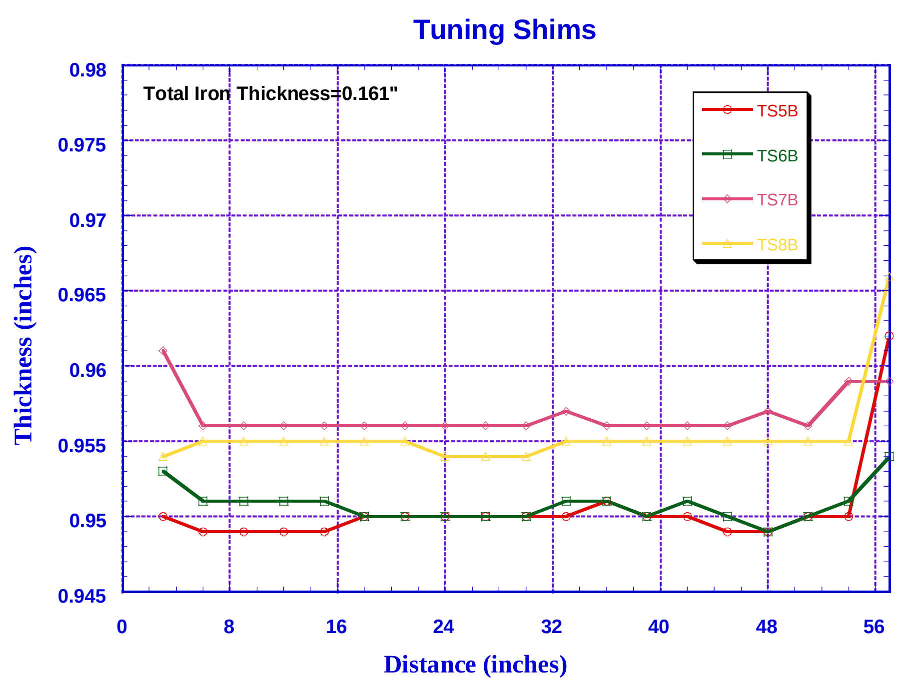

Fig. 7 The variation in thickness of the tuning shims along their length for the configuration with total iron thickness of 0.161”.

Bibliography

[1] G. Sabbi, “Proposal for HGQ experiments involving magnetic shims,” Fermilab TD-98-048, August 1998.

[2] G. Sabbi, “Correction of MQXB harmonics with magnetic shims,” Fermilab TD-98-047, August 1998.

[3] P. Schlabach, “Analysis of sextupole field distortions and snapshot events during testing of HGQ01 and HGQ02,” Fermilab TD-98-056, September 1998.