

## **FORMING AND WELDING OF NIOBIUM FOR SUPERCONDUCTING CAVITIES\***

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### **Summary**

Over the past two decades a variety of superconducting radio frequency structures have been designed, fabricated and tested, mostly in the pursuit of better and less costly particle accelerators. Over this period of time there has been an evolution in the fabrication processes as well as improvements in the test results. As in all technical endeavors, in the beginning fabrication was very difficult, but over the years developments in fabrication techniques have led to cheaper and improved structures in spite of the increases in the structures complexity.

This paper, which describes fabrication techniques, includes the description of work performed at many other laboratories as well as at Cornell. The author wishes to apologize to other laboratories for omissions, of which there are surely many. As far as disagreement on technical conclusions this paper describes those methods which have been found to be most satisfactory at Cornell as determined by our facilities and certainly does not claim that these findings would be the same in all other laboratories.

The author also wishes to thank all the other laboratories for sharing with Cornell the benefit of their experience over the years.

The types of forming which will be considered are:

- Machining
- Bending
- Spinning
- Deep Drawing
- Hydro-forming
- Hot Forming
- Explosive Forming

The types of joining which will be considered are:

- Explosive Bonding and Plating
- Electron Beam Welding (EBW)
- Tungsten Inert Gas Welding (TIG)
- Laser Welding

### **Machining**

The first Niobium structures which were fabricated and tested at Cornell were machined from solid Niobium material. Figure 1 shows an example of such an early structure. Half of a seven-cell, S-Band, "muffin-tin" structure is shown complete with machined filters at both ends which prevent RF leakage down the beam tube aperture.

The material cost and machining cost of such a structure were very high. However, a structure of this type was tested in the Cornell Electron Synchrotron and operated very well. [Ref. 1]

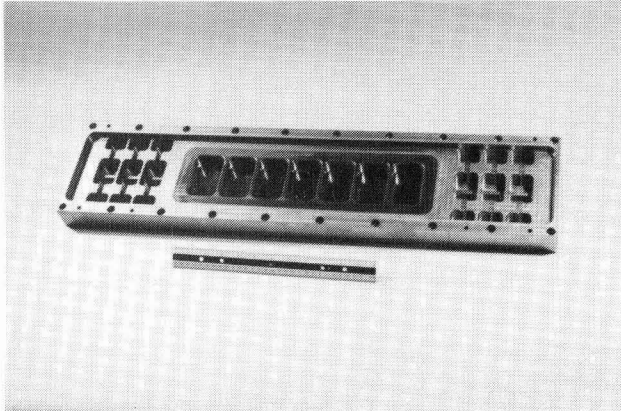


Figure 1.

The machining of Niobium has been described by some as having all the combined undesirable problems of stainless steel and soft copper. In spite of this, however, most shops have learned to machine the material with little or no difficulty. Several points make this required machining of Niobium possible and in some cases easier or more predictable than some other materials. These points are:

1. Flood cooling with Trichlorethane 1,1,1
2. Mill and lathe tools must have an extreme back rake angle (Aluminum cutting)
3. Cutting tools of high speed tool steel.
4. Cutting speeds of 80 SFM (25 m/min.) maximum.
5. Feed rates of 0.002 inches (0.05 mm) or less chip load, per revolution.

Internal tapping [especially blind tapping] remains difficult. External threading gives very nice results with roller dies. [Ref. 2],[Ref. 3]

There has been some Electrical Discharge Machining (EDM) done. Some of the Muffin Tin Shapes had a series of grooves (1.5 mm wide, 1.5 mm deep, and 3 mm spacing) cut in the bottom of the cups transverse to the beam direction. The grooves cut by EDM were used to prevent multipactoring in the cup bottoms. Ordinary EDM machines were used with highly filtered oil and copper electrodes. Currents of 10 amps average were used and material removal rates of 0.025 cu in per hour (400 mm<sup>3</sup> per hour) were experienced.

The need for material saving and the introduction of mass production called for advances in sheet metal techniques.

### Bending



Figure 2

Shearing and bending of Niobium sheet metal poses no particular problems. A variety of wave guide shapes as well as wave guide T's and elbows have been made with these simple techniques. The use of proper back gauges on a press brake will yield bends accurate in position to  $\pm 0.002$ " (0.05 mm). Figure 2 shows a transition beam tube and some wave guide sections made in this manner.

### Spinning

While spinning has been used extensively at other laboratories, [Ref. 4],[ Ref. 5] Cornell has had limited experience with this technique applied to Niobium. The disadvantages we have experienced are:

1. Need for intermediate anneals.
2. Lack of reproducibility.
3. Lack of in-house expertise

We realize that other laboratories do not share our experience and the technique has been applied with great success. Figure 3 shows a 4-cell cavity made with the spinning technique.

### Deep Drawing

Our first attempts at deep drawing were made when we were manufacturing S-band, "muffin-tin" structures. In a very short time we also applied the technique to X-band and L-band cups. Figure 4 shows a series of cups made during this period. [Ref. 6], [Ref. 7]

The dies were made of Copper-Aluminum Alloy (AMPCO) and most were drawn in a 2-stage process without intermediate anneals.

When the effort at Cornell switched from "muffin-tins" to elliptical circular cavities, the deep drawing was accomplished with single stage dies made (in house) from 7075-T6 Aluminum alloy. These cups were made in a variety of frequencies and thicknesses as shown in Figure 5. [Ref. 8], [Ref. 9]

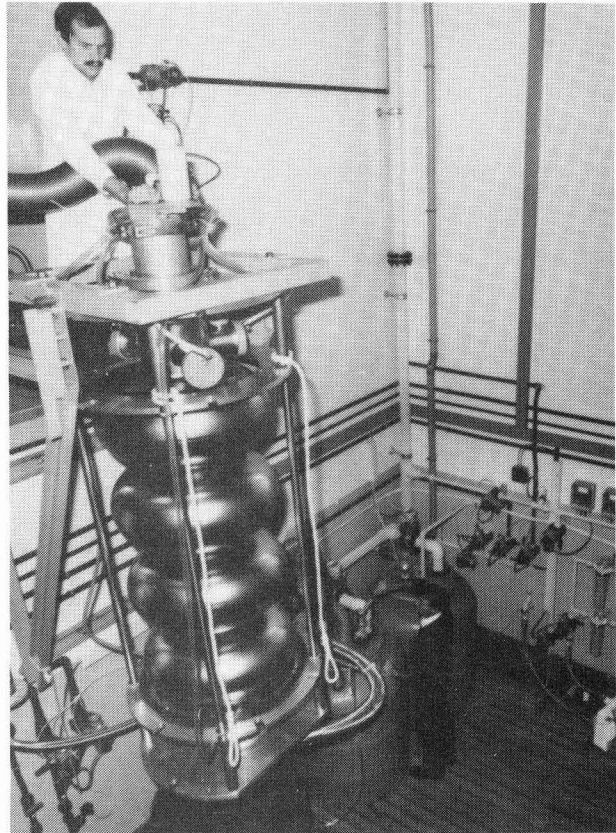


Figure 3

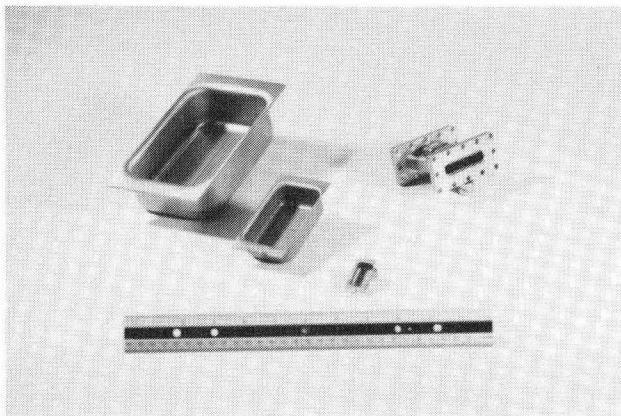


Figure 4

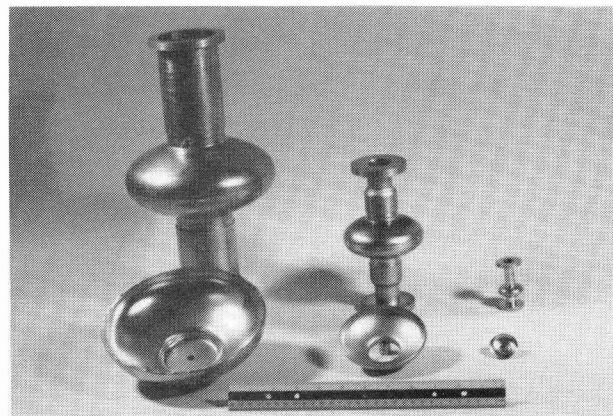


Figure 5

Most of the deep drawing was done using clean motor oil as a lubricant in order to avoid foreign inclusions. A typical L-band die is shown in Figure 6.

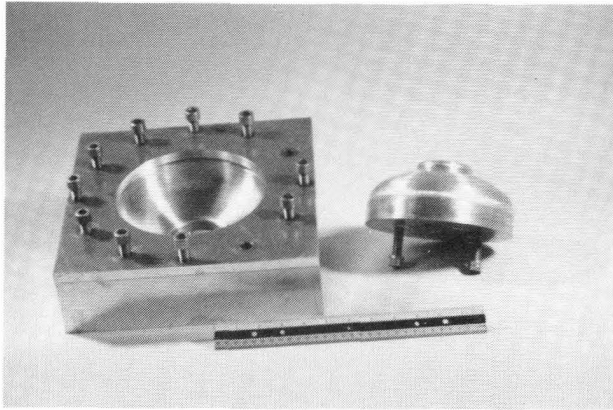


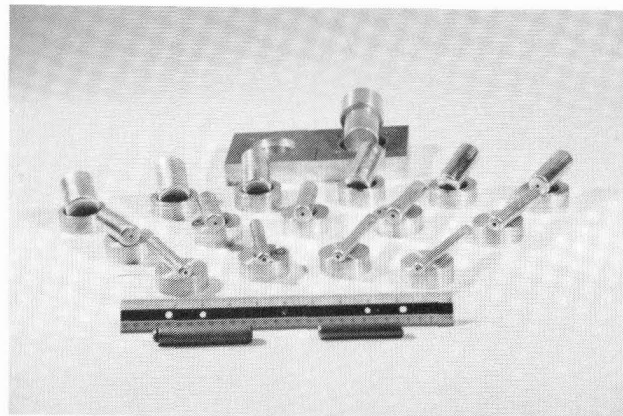
Figure 6



Figure 7

The die consists of three parts; a female die, a male die, and a bolted-on material hold down plate.

A variety of parts have been made by this process, all using aluminum dies with great success. Figure 7 shows a wave guide shorting dome, an HOM coupler body, and a cavity side port all made by the deep drawing process.



Several years ago an attempt was made in the laboratory to manufacture high purity tubing [high RRR] from flat Niobium sheet. A seven stage die set was made and used but the product showed excessive thinning and "orange peeling" even with two intermediate anneals. Another attempt was made with a very simple 16-stage die set and no intermediate anneals. To our surprise, the product showed no thinning or tendency to tear. Figure 8 shows the 16-stage die set as well as the product from the 7-stage and the 16-stage die set.

Our conclusion was that the metal deformation that could be achieved was a very strong function of the number of die stages that were used.

One disadvantage in the one stage deep drawing of the circular cavity cups has been a slight thinning of the material near the beam line nose. This thinning has made outside welding of the nose very difficult. Recently S-band cups have been made using a two-stage process. Figure 9 shows the contrast between the new 2-stage process and the old single stage process. Figure 10 is a picture of the dies used in the 2-stage process. The results of this effort will be discussed under Electron Beam Welding.

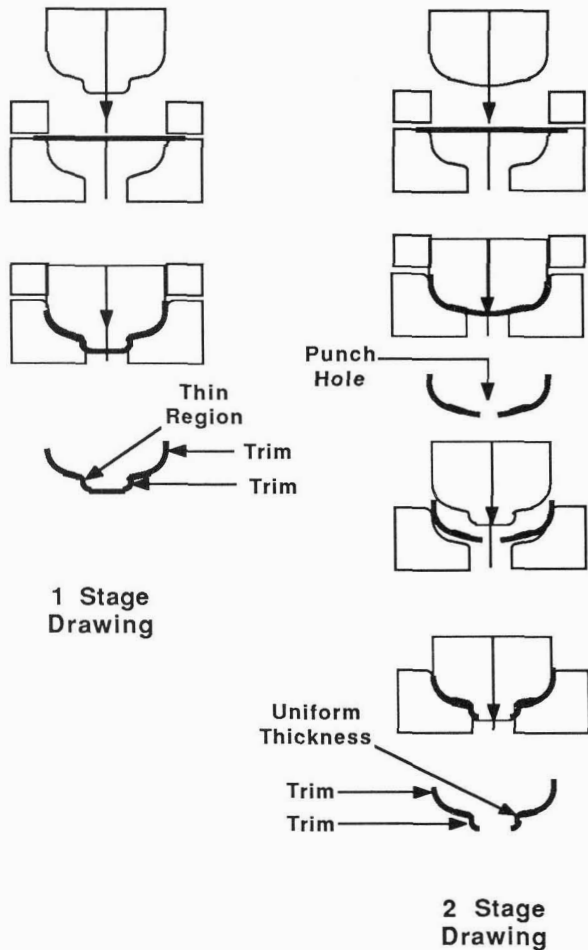


Figure 9



Figure 10

It should be mentioned that the interest in high RRR material in recent years has made more important the fact that intermediate anneals be eliminated in order to avoid decreases in the RRR. On the other hand, this high RRR material is much more difficult to produce with a small uniform grain size, so important in the deep drawing process. The final anneal must be controlled very closely in order to avoid excessive or non-uniform grain growth.

The general rules that may be followed for deep drawing are as follows:

1. Dies must be made of aluminum (7075-T6), AMPCO or Beryllium Copper. 7075 aluminum is by far the cheapest and easiest to machine, and has as high a yield strength as the other materials. Hundreds of pieces have made with such dies with no sign of die wear if adequate lubrication is used. Conventional die materials such as steel or Tungsten Carbide are not satisfactory as they tend to gall (friction weld) with the Niobium. This does not happen with the aluminum or copper base materials.

2. The die clearance which is used is equal to the material thickness. We have observed no excessive pinching or die wear.
3. A lubricant must be used. "Never Seez" works very well but can easily become contaminated with debris which will then be pressed into the Niobium surface. For this reason, clean, new motor oil is preferred.
4. Very simple "hold down" plates and hydraulic presses may be used. The use of a slow hydraulic press assures there will be no "stress rate" effects. Automatic hold down and stripping features would be significant only in very large production runs.
5. The ASTM metal grain size should be 4 or smaller in order to avoid orange peeling. This is sometimes difficult to achieve in the high RRR materials.

### Hydroforming

The differences and distinctions between deep drawing and hydroforming become somewhat vague. Hydroforming will be defined to be when one side of the worked piece is forced only by a fluid, whether it be hydraulic fluid, gas, or polyurethane. Some of the earliest Niobium cups were hydroformed by HEPL at Stanford [Ref 10].

Several years ago in our development of circular L-band structures, there was a tendency to experience magnetic breakdown at the equator weld. In order to avoid any welds in the high magnetic field regions of the resonant structure, we pursued a technique of hydroforming a complete multicell cavity from a seamless tube. We have formed such shapes with an ID:OD ratio of 1:3. The essentials of the technique are shown in Figure 11.

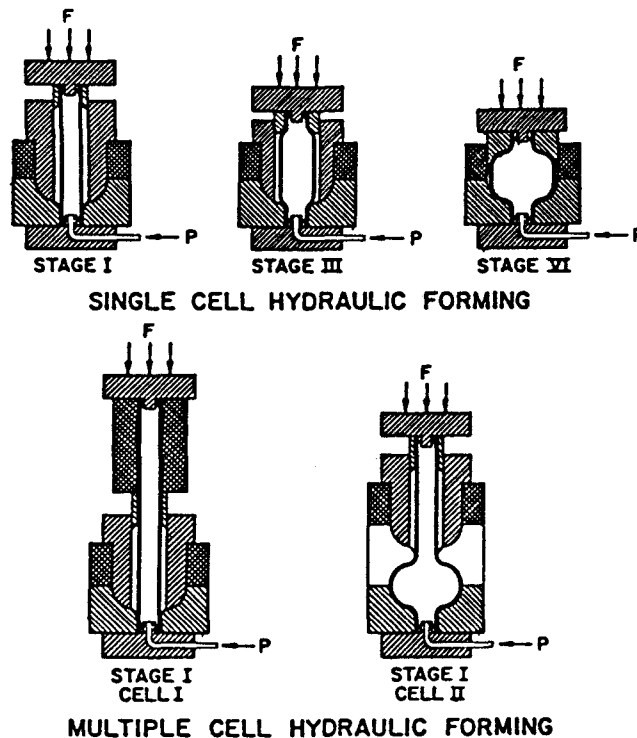


Figure 11

Multiple stages are required in order to avoid the lateral instability of the tube as axial force is applied. We found six stages to be satisfactory with an interstage anneal at every other stage. The chosen technique forms one cell complete at a time and imposes no limitations on the number of multiple cells which may be formed. While complete computer modeling of the process has not been done, calculations have been made which allow us to predict the thinning and buckling at each stage. Approximately 3% thinning per stage is our usual design goal. The development of a device to measure hydraulic fluid flow at 10 KPSI was necessary in order to monitor the process. The precision required on the fluid flow measurement was such that an analog computer was used to account for the compressibility of the hydraulic fluid as a function of pressure. Figure 12 shows several S-band size structures manufactured in this manner.

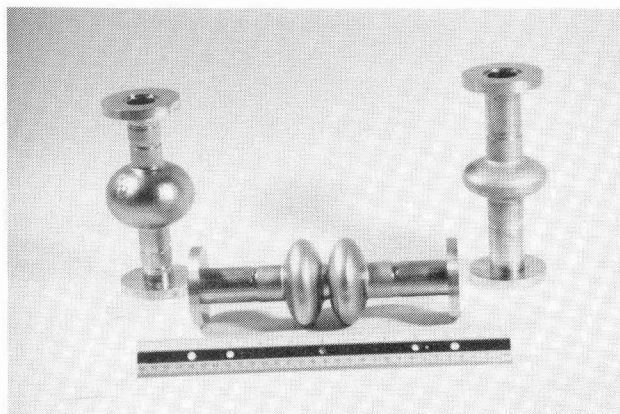


Figure 12

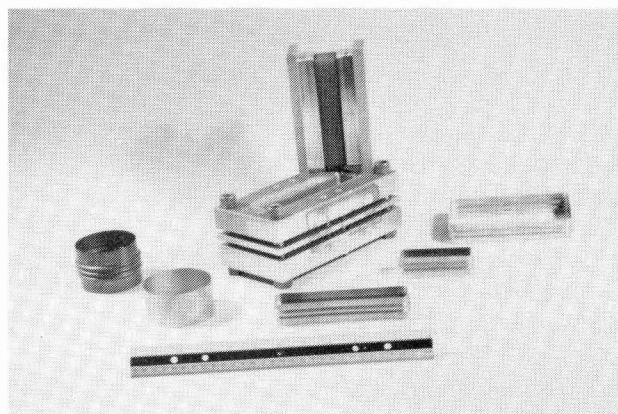


Figure 13

Cryogenic test results showed the typical cavity performance to be average even though the technique tended to give a very rough interior surface finish.

Our efforts were discontinued for the following reasons:

1. Improved welding techniques eliminated breakdown at the equator weld.
2. Seamless Niobium tubing of small, uniform grain size is expensive and difficult to acquire.
3. The cost of the dies, the labor of the process and the annealing cost were all much higher than the deep drawing, machining, and EBW costs of the present method.

Some other items have been made by hydroforming. Figure 13 shows a type of beam tube and wave guide bellows which have been made along with one of the typical die sets. A band of 0.015" thick Niobium is welded, then pressed axially as a polyurethane plug expands radially to form the convolutions. The die also collapses axially as this happens in order to avoid material being forced axially over the die convolution plates.

### Hot Working

Some tests were performed in order to determine the advantage, if any, of trying to blow bubbles in Niobium tubing at an elevated temperature. This work was done in a vacuum with high pressure (3 KPSI) Argon gas inside the hot Niobium tube. Tests indicated that at 800 deg C the % change in radius before rupture was the same as at room temperature. At 1200 deg C there was some improvement, but the gain certainly was not enough to warrant the continuation of the effort.

Hot Isostatic Pressing (HIP) has been tried as a way to produce parts of Niobium from Niobium powder. Photo-micrographs indicate that there are voids in the material. Cryogenic tests bear this out, as the test results have not been very good.

### **Explosive Forming**

Tests were also made to investigate any possible advantage in the very rapid cold working of Niobium due to a stress rate dependence of the % elongation. A small die was machined and primer cord explosive was used under water inside a 1.5" dia. Niobium tube. [Ref. 11] The results indicated that the % change in the tube radius before rupture was much less than the change achieved with a slowly applied force (hydraulic). The conclusion was that in the case of Niobium metal, the stress rate dependence is disadvantageous.

### **Bonding**

For reason of increased thermal conductivity, considerable work has been done with Niobium bonded to copper. Vacuum furnace brazing can be used, as well as "melt on" techniques. [Ref. 12] Some cavities have been made at CERN using this method. At DESY, work is continuing to plate copper and/or silver on the outside of circular cavities for reason of tube cooling. [Ref. 13].

The explosive bonding of copper to Niobium on one or both surfaces has been used extensively at Argonne National Lab. [Ref. 14] This method has also been used at Argonne to manufacture Niobium-lined copper tubes.

All the copper clad Niobium structures, however, have the difficulty of requiring that all copper be removed from the regions where the Niobium must be welded. Very slight traces of copper which might be present will ruin the material in the welds.

### **Electron Beam Welding [EBW]**

At the present time, most of the electron beam welding being done at Cornell is done in a full penetration, smooth underbead mode. [Ref. 15] This sort of weld parameter is used by many laboratories, achieved in a variety of ways. The method we use to "defocus" the beam is to deflect the beam in the shape of a rhombus with the beam deflection yoke. [See Figure 14]

This resulting reduction in the energy density gives a smooth underbead, but requires careful control of material thickness in order to achieve full penetration with no blow holes. Figure 15 depicts what is permissible in the way of material edge preparation for satisfactory welds. Material thickness uniformity is much more important than off-sets. This has led us to conclude that a square butt weld with no stepped edge machining is most desirable insofar as the material thickness remains uniform.

Figure 15 also shows the detail of the nose weld using 1-stage and 2-stage deep drawing. In the first case, we were forced to use an internal weld due to thinning on each side of the weld zone. With the 2-stage process this was not true, and satisfactory welds could be made from the outside. Figure 16 shows an S-band cavity with all welds made from the outside.

The only edge preparation after deep drawing was a facing of the cup. This technique should significantly decrease the cost of welding multicell structures.

The critical nature of material thickness when making the smooth underbead welds is unfortunate. Tests show the welds to be even more critical as the material thickness is increased. For this reason, the internal gun welding [as used at CERN] is desirable but cannot be used with the higher frequency structures.





Some tests have been made using the "rhombic raster" weld in conjunction with negative weld current feedback from a weld temperature sensor placed on the underside of the weld. [Ref. 16] This technique shows great promise, but a large development effort would be required for final utilization.

### **TIG Welding**

While at one time very popular, the use of TIG welding is rarely used because of the difficulty of excluding all air to a very high purity level from the hot weld in a reliable way. TIG welding does have the one advantage of giving a smooth underbead due to the lower energy density.

### **Laser Welding**

Laser welding of Niobium structures has not been utilized to any great extent. This has probably been due to lack of penetration and difficulty with surface reflection. If these problems were solved the results should be as good as EBW but any advantages are not obvious. The lack of such welding facilities at the laboratories will probably also slow the development of this technique.

### **Conclusion**

At the present time the utilization of RF Superconductivity is not limited by our ability to fabricate and weld the structures that are required. The required techniques are, however, sufficiently unique and specialized that it is difficult to find all the required facilities in one place other than at our own laboratories. Figure 17 shows some typical miscellaneous wave guide parts fabricated in our laboratory.

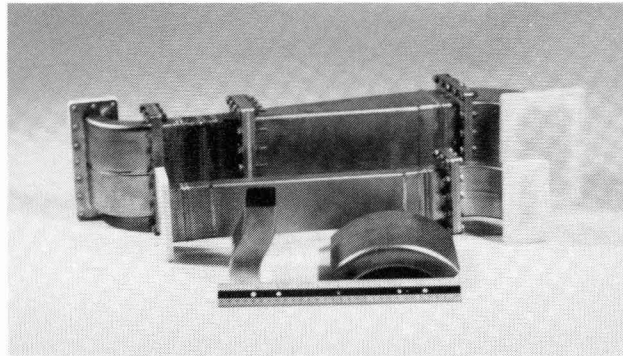


Figure 17

The fabrication of these parts required; machining, deep drawing, EBW, TIG welding, hydroforming, and bending as well as all the required intermediate chemical cleaning processes. This is typical of the complex structures and indicates the scope of the industrial involvement that will ultimately be required.

As one considers much larger accelerator projects involving superconducting RF there is no question but that the present designs must be altered to allow for much less expensive fabrication, both of the superconducting structures and of the auxiliary cryogenic and RF components. Such larger projects will require improvements in fabrication technology as much as they will require improvements in Q and voltage gradient.

### **Acknowledgements**

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