CEBAF Experience with In-House Production Fabrication of Niobium Parts

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Introduction

While the production fabrication of the CEBAF superconducting cavities was accomplished by a vendor, the niobium components which attach to the cavities were fabricated predominately using CEBAF in-house facilities. This paper describes the fabrication of the rectangular waveguide niobium Fundamental Power Coupler (FPC) extensions, the Higher Order Mode (HOM) coupler elbows, and the cavity pair connecting beam tubes (Figures 1, 2, 3). The machines required for this fabrication are listed, and the main machining parameters are given. There is a reference to the detailed procedures and the machine programs used during for fabricating these parts. The portion of the work subcontracted to outside fabricators is also included in the scope of this description.

The first few units were fabricated using methods not described here. The scheduled production was completed September 1993. The production sequence and the step-by-step procedure numbers are shown on the diagrams.

Parts Completed for Installation in the Accelerator

The full complement of 338 FPC extensions, 676 HOM elbows, and 119 beam tube assemblies have been completed for the accelerator cavities. An additional production run for spare parts with 20 FPC extensions, 40 HOM elbows and 10 beam tube assemblies is now underway. Fabrication errors, including welding, caused a loss of less than 1% of the total fabricated parts.

1. Rough Stamping, Cutting, and Forming of Niobium Parts

1.1 Rough Stamping

Rectangular niobium flanges up to 15mm (9/16 in) thick have been stamped by an outside fabricator. This is a very economical way to fabricate parts to rough dimensions and to punch out the bolt holes in the flange. Approximately 1700 rectangular flanges for the pair parts have been supplied to CEBAF as stamped parts. This technique permits salvage of scrap material for resale or credit with material suppliers.

1.2 Saw Cutting and Shearing

Thicker parts up to 38 mm (1 1/2 in) have mainly been saw cut. Abrasive water jet cutting was used in an early production phase.

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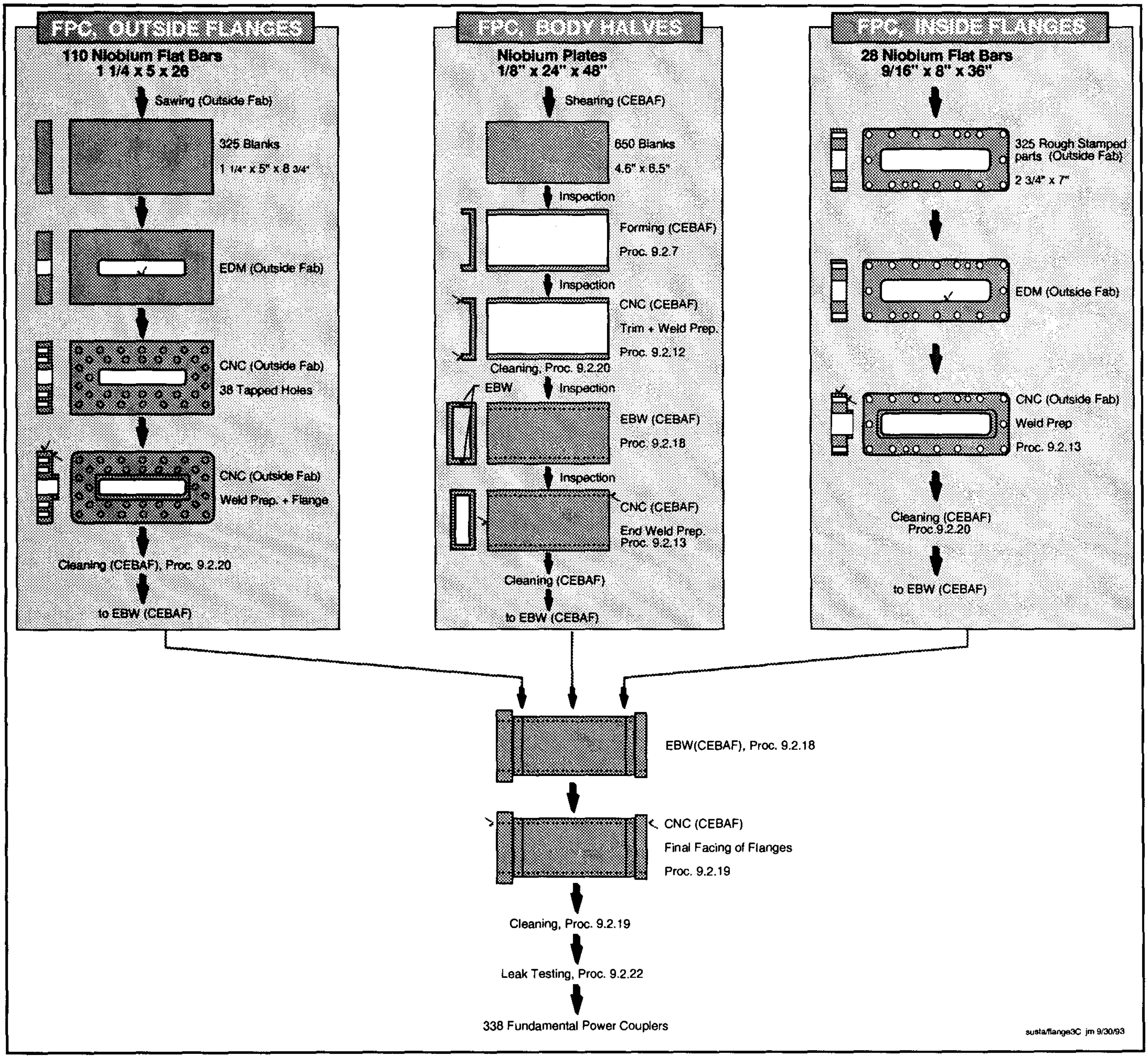

Figure 1. Fabrication sequence for niobium fundamental power coupler extensions

Parts made out of 3 mm (1/8 in) sheet have been sheared or bandsaw cut, depending on the contour geometry. One side of the niobium sheet is protected with vinyl tape to protect the surface during this fabrication. A carbon alloy blade with 3/8 in x 10 teeth/in with a cutting speed of 25–30 m/min (85–100 fpm) was used when sawing 3 mm (1/8 in) niobium material.

The shear used at CEBAF is a 151 bar (2225 psi) hydraulic shear.

The rough round flanges for the beam tube assemblies were saw cut from a round niobium bar.

1.3 Forming

Forming of niobium parts is done at CEBAF with specially developed fixtures.

The FPC extension body halves are formed in a 15 ton brake.

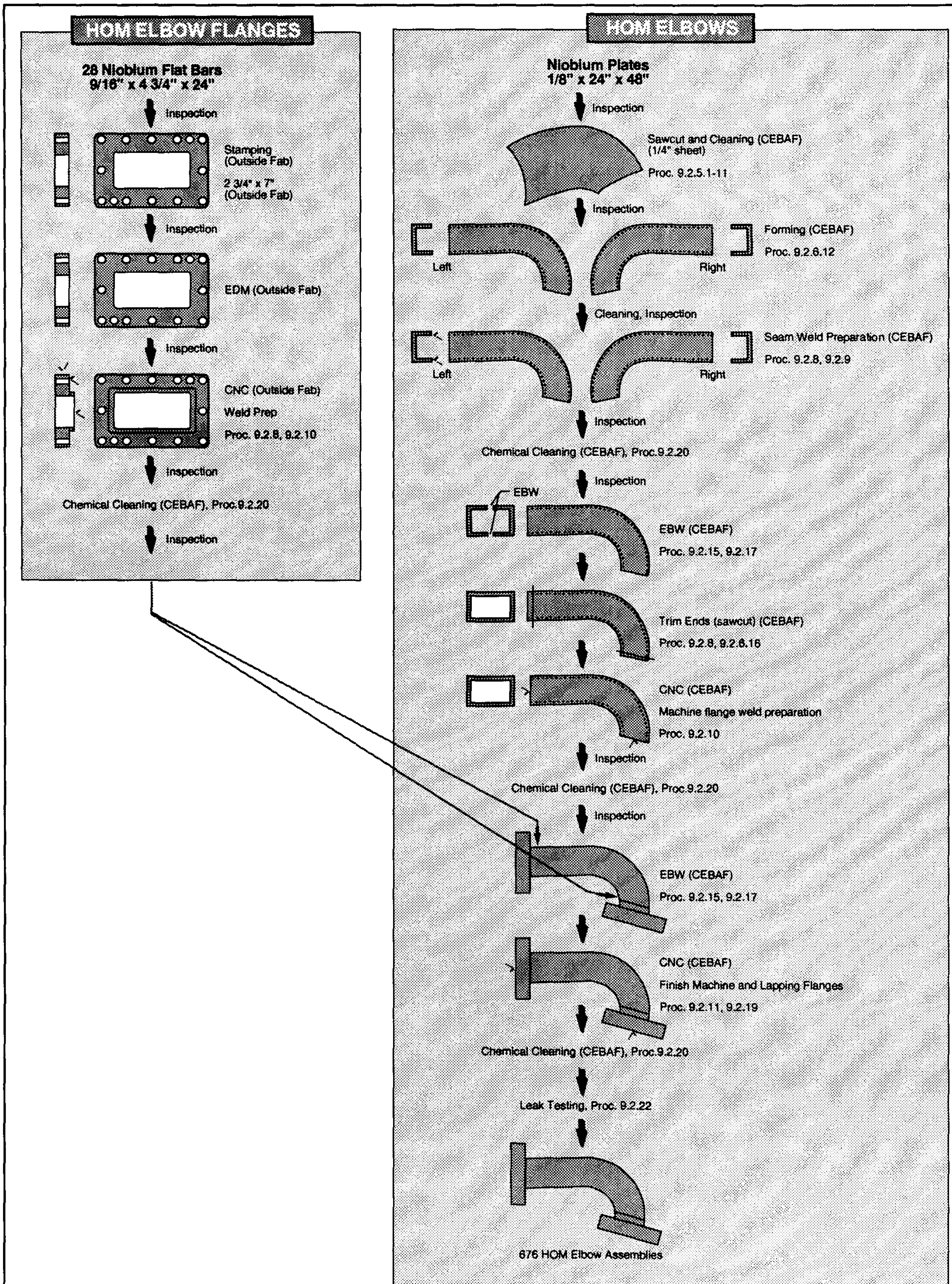

Figure 2. Fabrication sequence for niobium HOM elbows

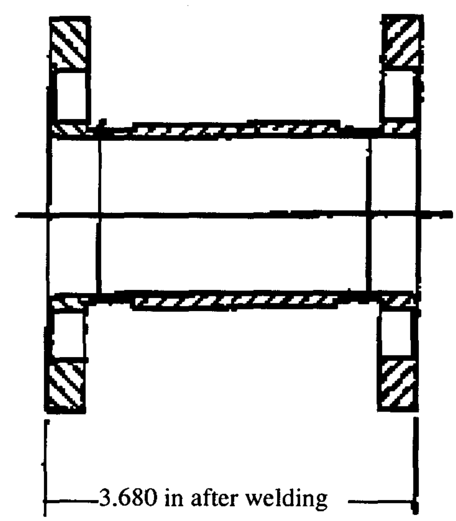

Figure 3. Niobium inter-cavity beam pipe

The HOM-elbow halves are pressed in a 150 ton press. Two pressing operations are required to avoid tearing and excessive stretching of the material. The dies are coated with an anti-seize lubricant (HI temp C5-A Fel-Pro) before the forming. The parts are then cleaned in a Kleer Flo, Cleanmaster model J80, 50 gallon cleaning machine, using Gray Mills M-8400 Super Agitene part-cleaning fluid.

- 1352 HOM-elbow-halves bodies were pressed.
- 776 FPC-halves bodies were formed.

2. Machining of Niobium Parts

2.1 Wire Electrical Discharge Machining (EDM)

EDM of niobium is a good option for machining deep through-holes with small radius or square corners to final dimensions. The machining speed for 25 mm (1 in) thick material is approximately 1.5 mm/min (1/16 in/min).

Speed can vary with the power of the machine.

This method has been used by an outside fabricator to machine the rectangular holes of the approximately 2000 FPC and HOM-elbow flanges.

2.2. Machining with the CNC-mill at CEBAF

2.2.1 Each FPC and HOM-elbow required the following milling work:

- two seam-weld preparations
- two end-weld preparations
- two flange facings

Approximately 6000 CNC machining steps were required of the CEBAF CNC-mill for the production of FPC's and HOM elbows.

2.2.2 CEBAF CNC-Mill Description:

MAZAK model AJV 25/404 CNC Machine Center (25 HP, Y=508 mm (20 in), X=1000 mm (39.4 in), Z=460 mm (18.1 in), 30 tools max.).

Positioning accuracy +/-3 μm (0.00012 in); position repeatability +/-1 μm (0.0002 in); fourth axis: 0.001 degrees least input increment.

2.3 Outside Flange Fabrication

Outside vendors have successfully machined niobium with some help from CEBAF. Several local machine shops were able to successfully produce production parts with very low scrap rate and without special pricing. The CNC mill used to machine rectangular flanges was similar to the one used at CEBAF.

The beam pipe flanges and tubes are lathe machined.

2.3.1 Flanges Required:

- 1352 HOM elbow flanges machined from stamped-out blanks
- 338 FPC outer flanges
- 338 FPC inner flanges
- 338 beam tube flanges

2.3.2 Flange CNC Machining Tooling Description

- Finish-cut face milling is done with 75 mm (3 in) and 125 mm (5 in) High Speed Steel (HSS) shell mills ground with zero degree axial rake angle, 20 degree radial rake angle, and 3 mm (1/8 in) corner radius. (Reference: ASM International Metals Handbook, 9th edition, V.16, Machining, ISBN: 0-87170-007 (V.1), page 865, Figure 6.)
- Rough-cut face milling is done with carbide shellmills 75 mm (3 in) and 125 mm (5 in), Mil-Tec mil-loc with Super Shear 3 mm (1/8) radius insert C-5, Sandvik T-Max 290 with WH or WM insert.

2.3.3 CNC Tool Feed and Speed Parameters

- Rough cut with carbide shellmill: 150 surface m/min (500 fpm) at 0.3 mm (0.012 in) feed rate.
- Finish cut with HSS shellmill: 37 surface m/min (120 fpm) at 0.15 mm (0.006 in) feed rate. The fourth axis is used for facing both ends of standard parts, and also to machine the FPC custom angles and tilts in one step.

2.3.4 CNC Machining of Weld Steps on Rectangular Flanges

- Parameters are the same as for machining of sheet metal seam and end weld steps 2.4.

2.3.5 Drilling for 3/8-16 Tapped Holes

Drill bit: High Helix 118 degree Point HSS (TiN coating optional).

Tool suppliers: Precision Twist Co., Greenfield Industries, Cleveland Twist Cutting Tool, Ex-Gold Drill HSS Cobalt, OSG Mfg. Company.

2.3.6 Tapping of 3/8-16 Blind Holes

In the past, the tapping of blind holes in niobium has been difficult, but with the new tap geometry it has become easier to achieve clean threads.

Tap geometry: Spiral fluted modified bottoming (3-4 pitch chamfer).

Tool suppliers: OSG Mfg. Co., EMUGE Corp., Greenfield Industries.

Tap speed for 3/8 -16 thread is 2.4 surface m/min (8 fpm).

2.3.7 Machining of beam tube Flanges and Tubes

The flange finish and the weld preparation are lathe machined.

2.4 CNC Sheet Metal Machining at CEBAF

To machine weld steps in 3 mm (1/8 in) material, the part must be mounted in a fixture that clamps the sheet metal close to the machining area. This prevents the sheet metal from moving with tool pressure. The tolerances were held to +0.025/-0.075 mm (+0.001/-0.003 in).

2.4.1 CNC Tooling for Seam and End Weld Preparation

-Straight endmills 3 mm (1/8 in), 9.5 mm (3/8 in), and 12.5 mm (1/2 in).
-Ball end mill 12.5 mm (1/2 in).
-Premium Cobalt 4 Flute (TiN coating optional).
-Tool brands: Cleveland Twist PM PLUS, OSG Exomill VC-10, and Putnam Mach IV.

2.4.2 CNC Tool Feed and Speed Parameters

For all tools up to 12.7 mm (1/2 in) dia: 42 surface m/min (140 fpm) at 0,2 mm (0.008 in) feed rate. All cuts to be clime cutting. Depth of cut for 3 mm (1/8 in) tools is 0.25 mm (0.01 in) maximum. Leave 0.12 mm (0.005 in) for the finish cut. "X and "Y" finish cuts can be cut at full depth of part.

Short lengths of waveguide can be fixtured so that they can be mounted on a 4th axis and rotated so that both ends can be machined with one setup.

2.5 Machining Coolants

2.5.1 CNC Flood Coolant

- Castrol Industrial Type SW-133-LF, mix 30 parts water to one part SW-133-LF.
- 1, 1, 1 Trichloroethane with 10% oil. This coolant has produced the best consistent surface finish, but was judged to not be practical in flood coolant systems due to rapid evaporation and resulting environmental hazards. Use of this coolant has been discontinued at CEBAF.

2.5.2 Tapping coolants

- Tapping Winbor Tapfree. Best for tapping. But contains 1, 1, 1 Trichloroethane, Methyl Chloroform, and Vinyl Ester. Supplier: Winfield Brooks Company.
- Tapmagic Extra. Contains no 1, 1, 1 Trichloroethane, supplier: The Steco Company.

3. Electron Beam Welding

Because niobium so readily forms brittle oxides, fusion welds are best accomplished in an electron beam welder. We chose to fabricate most of the auxiliary Nb parts using in-house capability which includes an electron beam welding facility. Strict adherence to quality-control procedures and multi-part (6 assemblies or more) welding requiring special fixtures allowed us to satisfy the needs of the cavity pair assembly production.

The equipment used is a CNC, moving-gun electron beam welder with a 1.73 x1.73 x 2.14 meter (68" x 68" x 84") vacuum chamber, located in a class 10,000 cleanroom.

3.1 General Procedures

Prior to welding, each part is cleaned with a buffered chemical polish solution (BCP).

Each part enters the EBW area via a class 1000 cleanroom. Prior to welding, parts are handled only with gloves; the piece is visually inspected for contamination and scratches; weld steps are then measured and rinsed with acetone, the parts are assembled and placed in the fixture, and the chamber evacuated. All welding is performed in a vacuum of 5 x10^{-5} torr or better. After the welding is completed, parts are cooled in the chamber for a minimum of 20 minutes. The chamber is then brought to atmospheric pressure with nitrogen. Welds are inspected for uniformity and full penetration then removed from the EBW area for further processing.

3.2 Fixturing

3.2.1 Beam Pipes - Figure 4

The main frame is 6061-T6 aluminum supporting 5 rotatable stainless steel shafts. Six beam pipes, centered by stainless steel spacers, are mounted on each shaft. They are spring loaded to take up weld shrinkage (approximately 0.25 mm (0.010")/weld). Sections of 3 mm (0.125") wall Nb tubing are slipped over each shaft to prevent contamination in the event of blow-through by the electron beam. The shafts are driven by a single stepping motor coupled through a speed reducer to a chain drive.

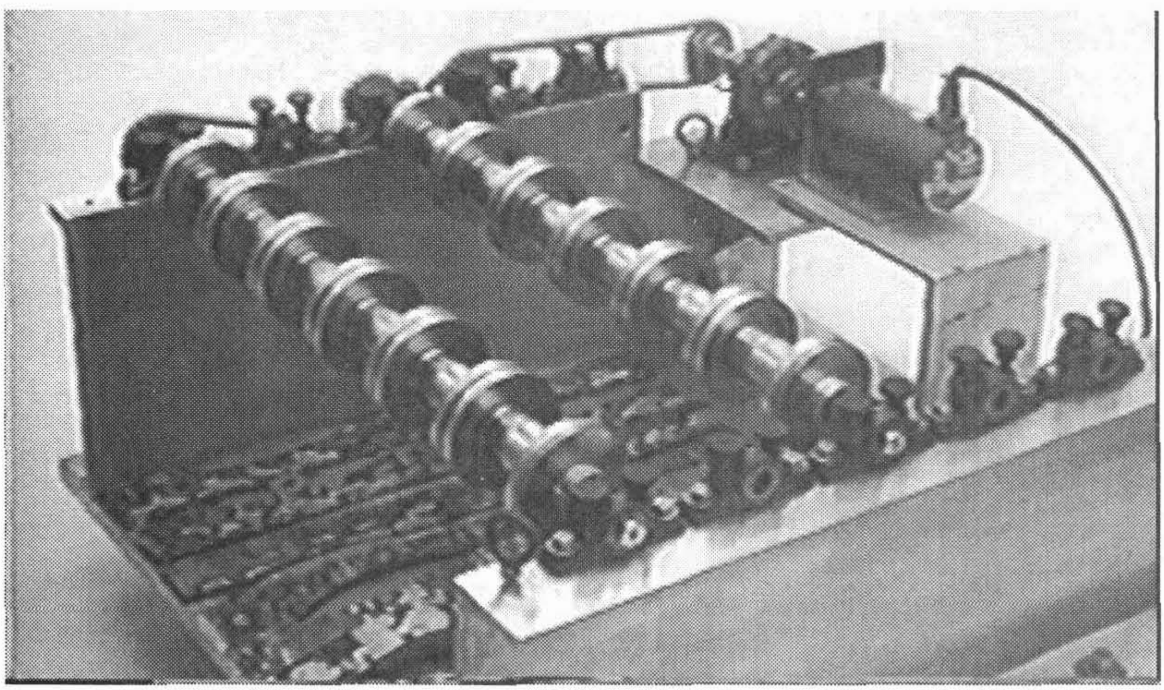

Figure 4. Welding fixture for niobium inter-cavity beam pipes

3.2.2 Elbow Halves

As with the beam pipes, the main frame is 6061-T6 aluminum. Elbow halves are placed in between spring-loaded aluminum plates and secured at each end by s/s threaded rods. The rods are covered with Nb to prevent contamination. Care must be exercised to ensure proper seating of the weld step prior to evacuating the chamber. The drive system is a stepping motor coupled to a transmission-type belt through a speed reducer. Although the fixture was built to accommodate 12 elbows, vision limitations due to metal evaporation on viewing ports made it more efficient to weld 6 at a time.

3.2.3 Elbow Flanges

The main frame is a 102 mm(4") aluminum channel with a center post mounted in a rotary chuck. Elbow flanges are secured to the body by a stainless steel threaded rod centered inside the elbow and fastened with stainless steel blanks at each end. An aluminum spacer is placed inside the elbow to maintain the rod in the center of the body. The elbow is fastened to the channel with stainless steel bolts through Nb run-off tabs. The tabs are in place to prevent the electron beam from striking the bolt heads and contaminating the weld. Six elbows can be mounted on this fixture.

3.2.4 FPC Extension Bodies

FPC extension bodies require no special fixturing. Normally 12 are welded per pump down.

3.2.5 FPC Extension Flanges

FPC extension flange welding uses the same fixture as the beam pipes. The fixture holds 8 FPC extensions at a time. See Figure 5.

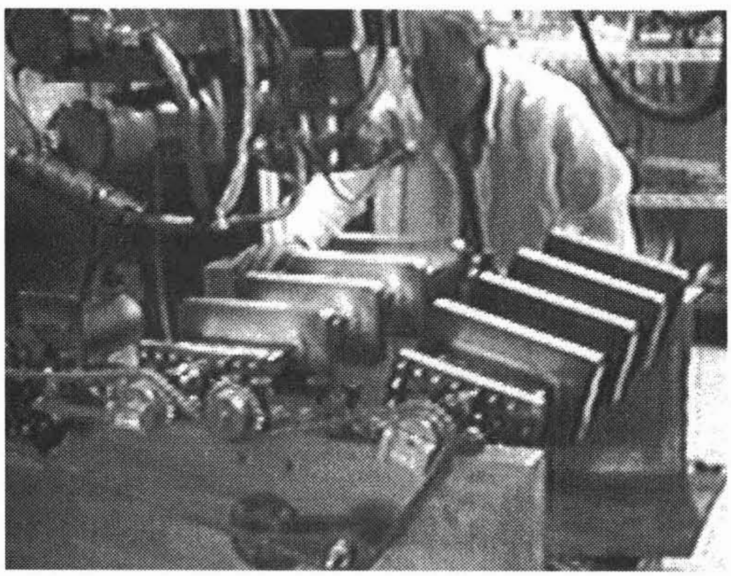

Figure 5. Electron beam welding fixture for FPC extensions

3.3 Welding—Beam Pipes, Elbows, and FPC Extensions

3.3.1 Weld Preparations

Initial joint alignment for all of the welds utilizes a video camera located inside the electron gun; scanning programs are used locate the joint ±.03 mm (0.001").

In all cases, running tacks are used prior to welding.

A low current (20ma) seal pass is used prior to welding to ensure proper fit-up of the joint.

3.3.2 Weld Parameters

The weld requirement is: 1.6 mm (0.062") full penetration, flat, smooth underbead, no weld spatter and approximately equal top and bottom bead width. -

- This is accomplished with a 10kHz, oval pattern, focused beam, approximately 4.6 mm (0.187") wide x 2.3 mm (0.090") deep.
- The beam is offset to compensate for the step joint (Figure 6).

- The weld parameter used in almost all cases is: 50 kV, 40 mA, 457 mm/m (18 in/min), with a gun-to-work distance of 152 mm (6").

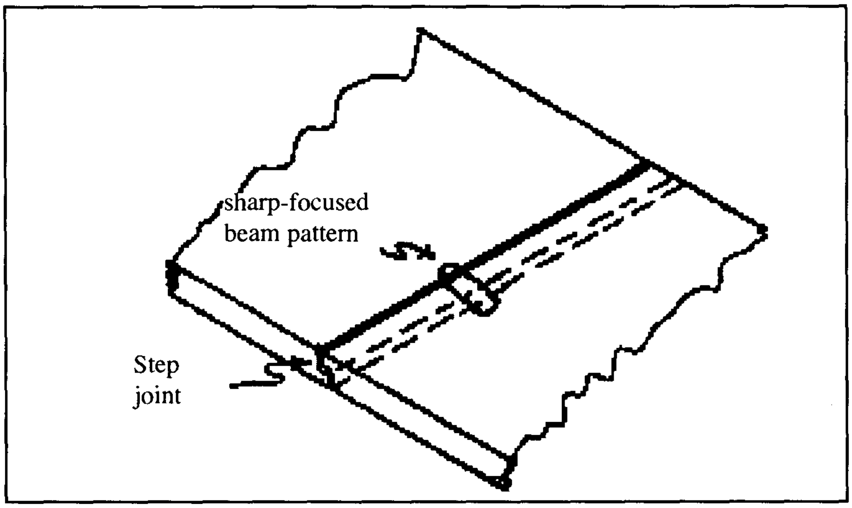

Figure 6. Electron beam weld geometry

3.4 Welding—Cold Rf Windows

All RF windows were welded in-house. The following is a brief summary of how this was accomplished.

3.4.1 Window weld fixturing—Figure 7

The window fixture is an aluminum plate (6061-T6) machined and doweled to seat 10 windows.

- Machined OFHC copper blocks, 6 mm (0.25") thick are placed precisely over the ceramic windows; they are held in place by hold-down clamps.
- The blocks have fiducials machined into the top surface and are used for heat sinking the.13 mm (0.005") eyelet, protecting the ceramic window and beam alignment.

3.4.2 Weld Geometry—Windows

The window weld consists of joining a ceramic window brazed into a 0.13mm (0.005") thick Nb eyelet to a 35 mm (1.375") thick Nb frame. The joint must be flat, smooth and leak tight.

The copper heat sink covers the ceramic and all but 1 mm (0.040") of the eyelet. The block is secured by an aluminum hold-down clamp covered with 3.2 mm (0.125") Nb in the weld area.

A focused electron beam is centered on the exposed section of the eyelet. Beginning in one corner the beam follows a race-track pattern around the eyelet, tapering to 0 ma after overlapping the start point. The electron gun is tilted 20 degrees and the section underneath the hold-down clamp is welded. See Figure 8.

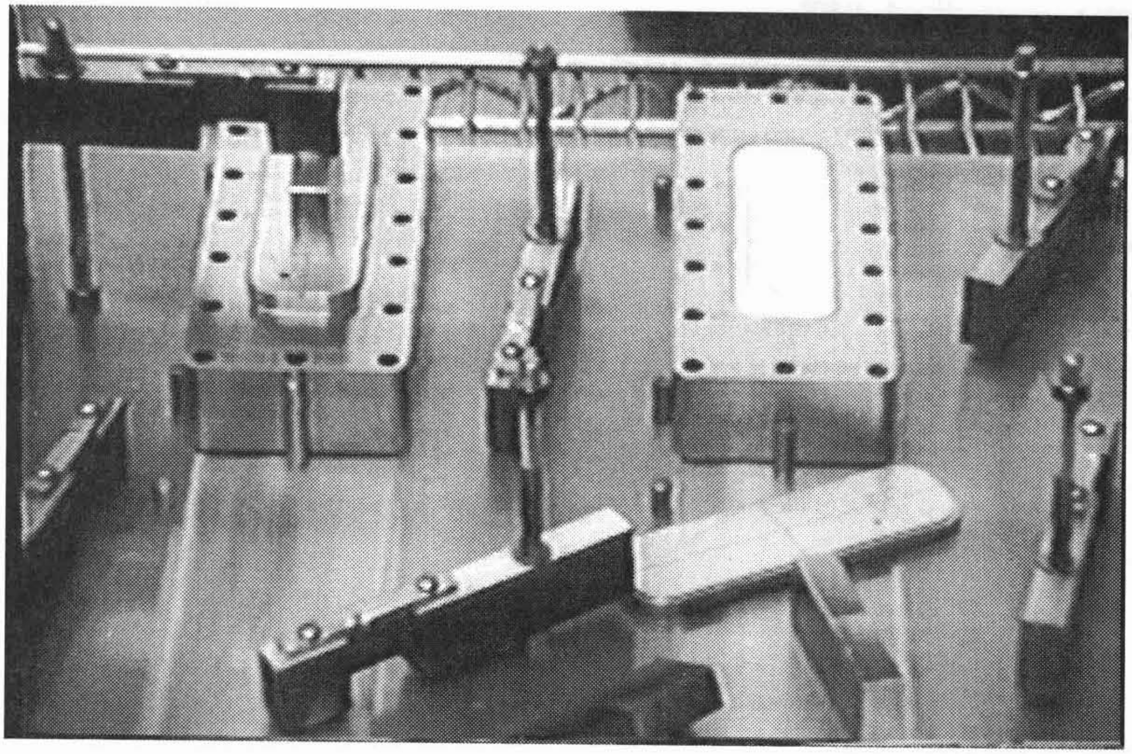

Figure 7. Electron beam welding fixture for rf windows

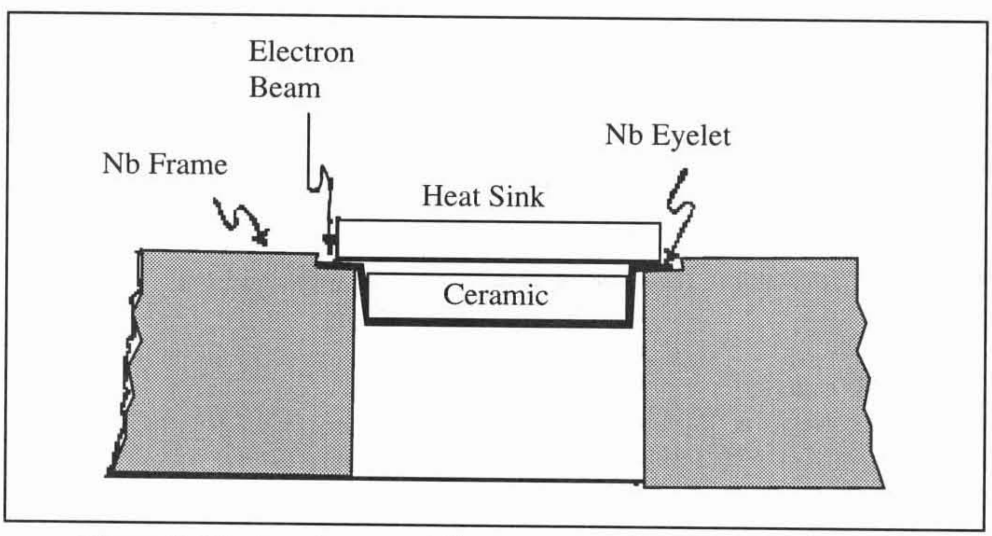

Figure 8. Electron beam welding geometry for rf windows

3.4.3 Weld Parameters—Windows

Beam parameters are: 50 kV, 25 mA, 508 mm/m (20 ipm), gun-to-work distance of 152 mm (6").

3.5 Welding Summary

The production welding of niobium pair parts began in late 1990 and was completed in September 1993. During that time 10,478 individual joints were welded to make 676 elbows, 338 FPC extensions, and 169 beam tubes. Within that same time frame, 338 windows were successfully welded with less than 4% failure. The problems encountered with windows were primarily contamination of the weld area by braze material and hydrogen embrittlement by previous heating in air atmosphere.

4. Lapping of Flanges

After final machining, all flange faces were lapped to insure that the flange surfaces are planar and scratch-free with a finish of 1.3 μm (32 μin) R_a or better. The lapping is done in several steps with wet sanding discs on a rotary table—120 grit, 240 grit, 14 μm (360 μin), and 1.2 μm (30 μin).

5. Cleaning Procedure

- Rinse in hot water.
- Immerse in degreaser ultrasonic for 5–10 minutes.
- Rinse with hot water, then let dry.
- Dip in BCP solution (H_3PO_4, HNO_3, HF in 1:1:1) for less than one minute.
- Rinse with ultrapure water.

6. Leak Checking

A mass spectrometer with a sensitivity $<1\times10^{-10}$ atm-cc/sec was used.

The test items are covered with a container filled with helium for 5 min during the challenge leak test.

Of the more than 1173 finished parts, 3 were found to have leaks.

7. Inspection

After each machining, cleaning, or welding step, each part was visually inspected for contamination and dimensional irregularity.

Acknowledgments

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