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MANUFACTURING OF NEUTRAL BEAM SOURCES AT LAWRENCE LIVERMORE LABORATORY

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Summary

Over 50 neutral beam sources (NBS) of the joint Lawrence Berkeley Laboratory (LBL)/Lawrence Livermore Laboratory (LLL) design have been manufactured, since 1973, in the LLL Neutral Beam Source Facility. These sources have been used to provide start-up and sustaining neutral beams for LLL mirror fusion experiments, inlcuding 2XIIB, TMX, and Beta II. Experimental prototype 20-kV and 80-kV NBS have also been designed, built, and tested for the Mirror Fusion Test Facility (MFTF).

The Neutral Beam Source Group provides services of engineering design, manufacturing, assembly, and maintenance of NBS for all programs at LLL. Some special methods, equipment, and techniques developed for manufacturing NBS accelerator assemblies are described in this paper.

We are building, at the present time, the third generation of the LBL/LLL designed NBS. The accelerators for these sources have spherically-curved grids that must be manufactured and aligned to tolerances typically in the 0.002 to 0.004 inch (0.05 to 0.10 mm) range over apertures of 7 x 35 cm or 10 x 45 cm in size. Critical machining operations are involved in generating long-radius (i.e., 3 to 10 m), cylindrically-curved surfaces for mounting the grid wire holders and in making the holders themselves. Special measuring machines have been developed for aligning individual grid wires and for the final alignment of completed three or four grid assemblies.

Introduction

Neutral beam sources are "fuel injectors" for magnetic fusion devices. They inject deuterium into a magnetic confinement region. There are three basic requirements for fuel injection:[1] the deuterium must be electrically neutral to penetrate the magnetic confinement field; the neutral deuterium ions must be energetic enough that they penetrate into the plasma and either heat it or replenish energetic ions lost from the plasma; and the source must focus and aim the neutral beam so that it intersects the hot plasma at the proper location.

The NBS is made up of two major subassemblies: the arc chamber, which provides the source of positively-charged ions, and the accelerator, which accelerates and focuses the ions into the hot plasma of the fusion device. When the NBS are used for <u>mirror</u> fusion devices, the accelerating and, in particular, focusing requirements impose stringent limits on the manufacturing and assembly technologies that can be used to construct accelerator assemblies. These limits are reflected in very close tolerances of form, fit, and position of individual parts and of major units, such as accelerator grids. Some special methods, equipment, and techniques developed at the Lawrence Livermore Laboratory for manufacturing NBS accelerators are described in this paper.

The Neutral Beam Source Group provides services of engineering design, manufacturing, assembly, and maintenance of neutral beam sources for all programs at LLL. We are building, at the present time, the third generation of the LBL/LLL designed NBS. The accelerators for these sources have <u>spherically-curved</u> grids that must be manufactured and aligned to positional tolerances, typically in the 0.002 to 0.004 inch (0.05 to 0.10 mm) range over apertures of 7 x 35 cm or 10 x 45 cm in size (see Figs. 1 and 2). Critical machining operations are involved in generating long-radius, (i.e., 3 to 10 m), cylindrically-curved surfaces for mounting the grid wire holders and for making the holders themselves. Special measuring machines have been developed for aligning individual grid wires and for the final alignment of completed three or four grid assemblies.

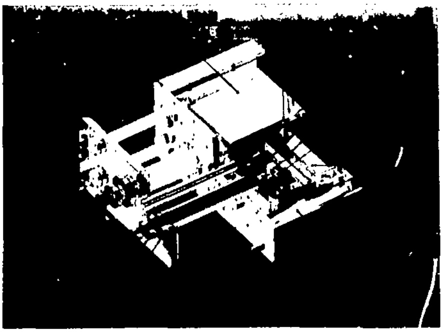

Figure 1. MFTF 80-kV Neutral Beam Source

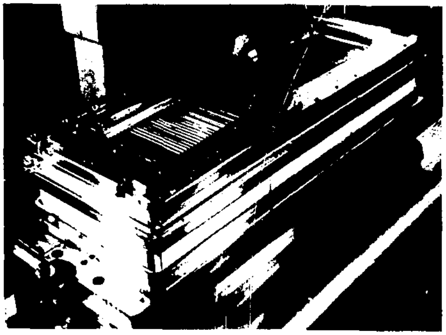

Figure 2. Four-Grid Accelerator for 80-kV Neutral Beam Source

Fabrication and Machining

<u>Grid Wires</u>. Individual grid wires have typical cross-sectional shapes as shown in Figure 3. The top wire (entrance grid) is trapezoidal in cross section and is formed from circular-section molybdenum wire by cold rolling. The two round section wires are formed by centerless grinding tungsten rod. The third wire from the top (pear-shaped) is formed by four stages of shaped die drawing.

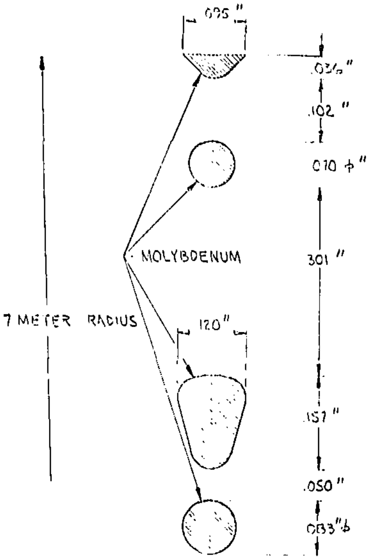

Figure 3. Cross-Sectional Shapes of Grid Wires Used in MFTF 80-kV NBS

The rolling mill we use to form the trapezoidally-shaped wires is shown in Figures 4 and 5. The bottom roll has a groove ground to the proper trapezoidal shape. The top roll is cylindrical (not grooved). With the rolls driven at constant speed, the circular-section wire stock is fed into the V-shaped entrance guide (see Fig. 5) with constant back-tension applied by a hanging weight, shown in the right side of Figure 4.

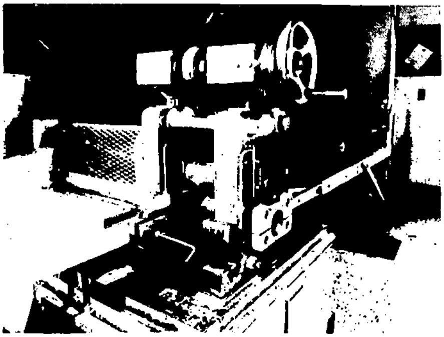

Figure 4. Rolling Mill Used to Form Trapezoidal-Shaped Grid Wires

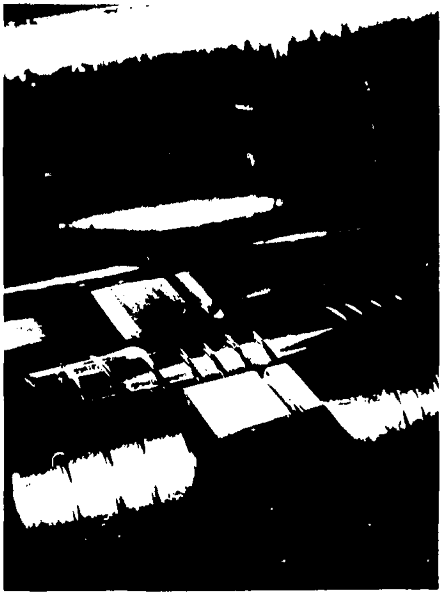

Figure 5. Guides and Grooved Roll Used for Grid-Wire Forming (Upper Roll is Shown in Lifted Position)

The straightness of the formed wire is controlled by precise, two-dimensional positioning of the grooved entrance and exit guides, relative to the groove in the lower roll. Guide supports must be of rigid construction and provide positional accuracies of 0.0001 inches (0.0025 mm).

The final cross-sectional shape of the rolled wire was found to be a function of: cross-sectional shape of the lower roll groove; smoothness of the groove sides; diameter of the circular wire stock; metallurgical properties of the wire stock (i.e., yield point, grain structure, impurity content, etc.); applied back tension; and lubricity of lubricant applied between the roll and wire stock.

We used trial-and-error methods over a period of several years to determine the necessary limits and controls of the above six variables to enable us to produce precision-shaped grid wires with cross-sectional contour accuracies of 0.0005 to 0.002 inches (0.01 to 0.05 mm) and a straightness of 0.002 inches (0.05 mm) over a wire length of 5 inches (127 mm).

The wire cross-sectional shape is measured at 50X magnification on a comparator using a computer-generated mask of the nominal cross-sectional shape. Wire straightness is measured with special gaging equipment designed and built at LLL for this purpose (see Fig. 6). The sensor for this gage is a linear variable differential transducer (LVDT) having a contact pressure of two grams or less and read-out accuracy of 0.0001 inches (0.0025 mm).

Machining. As mentioned in the above summary, the present generation of LBL/LLL designed NBS has accelerators constructed with spherically-curved grids. Curvature in the short dimension (i.e., width) of the aperture is obtained by elastically bending the grid wires. This method of curving and supporting grid wires was originated by LLL and has been successfully used in all LLL neutral beam source accelerators for the past six years.[2] The desired curvature is obtained by machining the proper angle in the socket, or slot, of the holders that support the grid wires at each edge of the aperture.

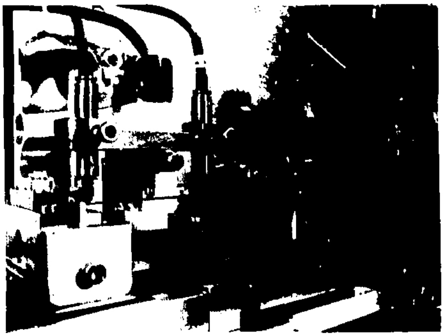

Figure 6. Special Gage for Measuring Straightness of Grid Wires

Curvature in the long dimension (i.e., length) of the aperture is obtained by bending the grid wire holder and clamping it with screws to a precision-machined, long-radius, curved surface. These curvatures range from 126 inches (3200 mm) to 276 inches (7000 mm).

Grid wire holders are machined in a continuous-path, computer numerical-controlled (CNC), three-axis milling machine. A typical machine setup is shown in Figures 7 and 8. A special fixture was built to mount and clamp the rough-machined, grid-wire-holder blank. This fixture is mounted on a precision (ten inch) sine plate, which in turn is clamped to the mill table.

Figure 7. CNC Three-Axis Milling Machine Setup for Machining Grid-Wire Holders

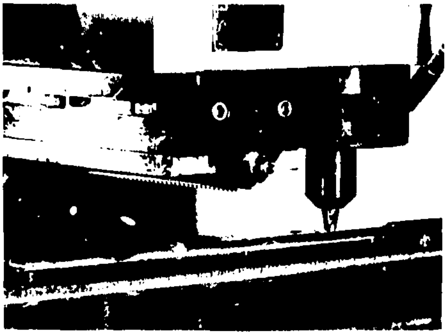

Figure 8. Grid-Wire-Holder Machining Showing Integral Mounting of Milling Cutter and Slot Broach

The machining operation is as follows: the vertical slide of the mill table is clamped to the machine ways, and the sine plate is clamped with zero tilt angle. Critical location surfaces are machined with the vertical-spindle milling cutter. The milling cutter is removed and the proper angle (typically 1.0 to 1.25 degrees) is set on the sine plate using precision gage blocks. The sine plate is then clamped at this fixed angle. The shaped grid-wire sockets are cut by broaching. All machine motions for milling and broaching are CNC.

We assign an error budget of 0.0003 inches (0.0076 mm) to the true position of all sockets in the grid-wire holder. This is obtainable with a good quality commercial milling machine such as that shown in Figure 7, provided that the unidirectional repeatability (x-axis motion of the mill) is within this allowable positional error, and point-to-point corrections are made for lead screw and other x-axis positional errors. Another desirable feature of the tooling setup is to mount the broach adjacent to the milling cutter and rigidly clamp it to the vertical spindle case. This can be seen in Figures 7 and 8.

We used a laser interferometer with a least count of 10^{-6} inches (0.000025 mm) to measure the point-to-point positional error in the x-axis of the milling machine and then programmed the appropriate individual correction for each of the 90 grid-wire sockets in the wire holder shown in Figure 7. We also used this same laser interferometer to calibrate our optical measuring machine shown in Figure 16 (this measuring machine is described later in this paper).

With these methods and tooling, we were able to reduce a cumulative error of 0.005 inches (0.127 mm) in 15.5 inches (394 mm) in X travel of the milling machine, to a maximum error of 0.0003 inches (0.0076 mm). This was determined by measuring the position of all 90 broached sockets in the finished wire holder, using the calibrated optical measuring machine (Figure 16). Approximately 80 sockets had positional errors of 0.0002 inches (0.0051 mm) or less, and 10 sockets had errors of 0.0003 inches (0.0076 mm).

Broaches are designed and constructed at LLL by form-grinding a dovetail shape for trapezoidal cross-section grid wires, and an octagonal shape for circular cross-section wires. Each tooth cuts a chip about 0.002 of an inch (0.051 mm) deep. The grid-wire socket is cut in a single pass of the broach. A typical broach is shown in Figure 9.

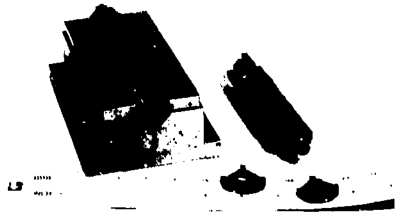

Figure 9. Broach Used for Cutting Slots in Grid-Wire Holders

The long-radius, cylindrically-curved surfaces used for mounting the grid-wire holders are machined in two steps on a continuous-path, three-axis, CNC milling machine. The operations are shown in Figures 10, 11, and 12.

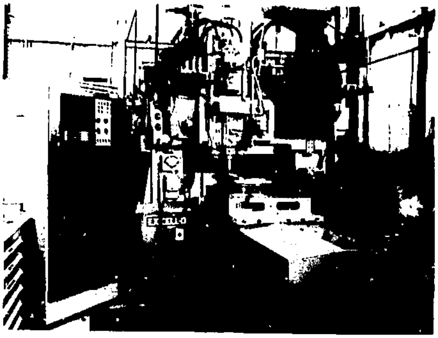

Figure 10. Continuous-Path, Three-Axis, CNC Milling Machine Setup for Machining a Long-Radius, Cylindrically-Curved Surface

The first step is to rough-machine the surface using a square-ended milling cutter (Figs. 10 and 11). This operation leaves a "cusp" or trough at each end of the surface, since the axis of rotation of the end mill is normal to the surface only at the center of the part. Final finishing to a true cylindrically-curved surface is accomplished by planing with a chisel-pointed tool (Fig. 12). The planing tool must be kept very sharp, and only cuts of the order of 0.0001 inches (0.0025 mm) should be used. With this method, we routinely machine both grid-wire-holder mounting surfaces so they will fall between two imaginary cylindrical surfaces separated by only 0.0003 inches (0.0076 mm).

The milling machine shown in Figure 10 is a bridge-type mill with a CNC controller having a least count of 10 micro inches (0.000254 mm) and a positional accuracy of about 150 micro inches (0.0038mm). However, we have successfully machined these same long-radius, curved surfaces in copper with a good quality continuous path CNC three-axis mill having a controller with a least count of 100 micro inches (0.00254 mm) and a positional accuracy of about 250 micro inches (0.0064 mm).

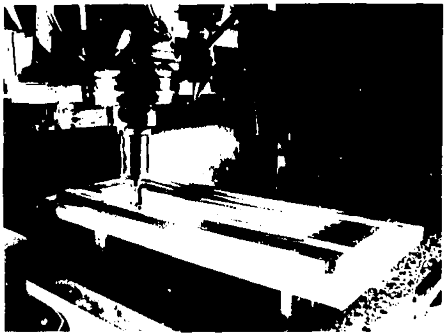

Figure 11. End Milling a Long-Radius, Cylindrically-Curved Surface in a Continuous-Path, Three-Axis, CNC Milling Machine

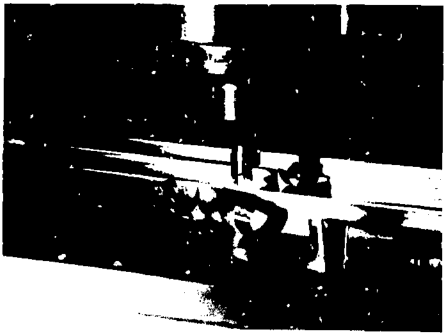

Figure 12. Finishing an End-Milled, Long-Radius, Cylindrically-Curved Surface by Planing in a Continuous-Path, Three-Axis, CNC Milling Machine

Assembly and Testing

Cleaning and Inspection. After machining, parts are deburred, cleaned, and inspected. Conventional metrology is used, including surface plates, a digital height gage, micrometers, gage blocks, and an optical comparator.

Preliminary cleaning includes vapor degreasing with perchlorethylene and washing with detergent and hot deionized water. Deburring is done with files and cutters, and by electropolishing for some parts. We use no abrasives and no sand or bead blasting. Final cleaning, after inspection, is done by ultrasonic cleaning in detergent and deionized water, or in petroleum ether, acetone, or alcohol. We also use chemical cleaning with ammonium persulfate.

Accelerator parts, such as molybdenum and tungsten grid wires and molybdenum masks, are given a final cleaning by firing in a hydrogen furnace at a temperature of 850 degrees centigrade for one-half to one hour.

After final cleaning, parts are bagged in clean plastic containers and stored in special cabinets located in the assembly clean rooms.

Assembly. Accelerators and arc chambers are assembled in separate clean rooms, shown in Figures 13 and 17, respectively. These cleanrooms are constructed for horizontal flow of filtered air and operate under a slight positive pressure. Assembly personnel wear lint-free cover clothing and use surgical gloves while performing assembly and alignment operations in these rooms.

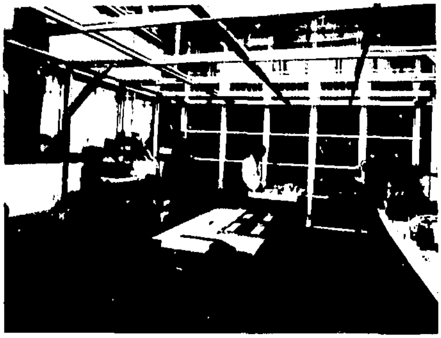

Figure 13. Clean room used for assembly and alignment of grids.

Accelerator grids are assembled and individual grid wires are aligned using special measuring machines built at LLL. One of the three machines we have constructed for this purpose is shown in Figures 14 and 15.

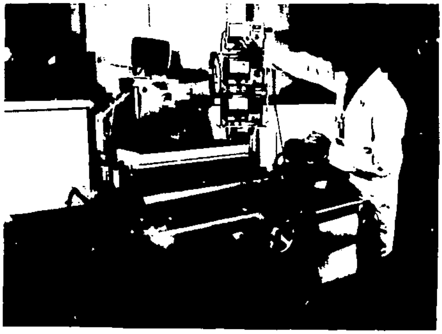

Figure 14. Special measuring machine used for alignment of individual grid wires.

Figure 15. Cam-controlled measuring head used for alignment of individual grid wires.

The base pedestal and table of the measuring machine are parts of a commercially obtained grinder. The measuring head is constructed using three linear variable differential transducers (LVDT) mounted on a common frame, which can be moved vertically, with an attached digital micrometer. The amplified output of the LVDT's is recorded on a three-pen strip chart with a scale factor of one inch (25.4 mm) of pen travel equal to 0.001 inch (0.0254 mm) of LVDT vertical motion.

The common frame holding the three LVDT's has a cam-controlled vertical motion to compensate for the curvature of the grid in the long direction (length) of the aperture. The sagittal height of each grid wire, at five separate locations, is measured and recorded as the grid is moved horizontally under the sensors. The curvature of an individual wire is changed when necessary by plastically deforming the copper wire holder a slight amount, using a steel punch and small hammer.

When all wires are properly aligned, their top surfaces or common centerlines will fall between two imaginary spherical surfaces separated by 0.002 to 0.004 inches (0.05 to 0.10 mm) over the full area of the aperture (i.e., 7 x 35 cm or 10 x 45 cm).

The last major step in accelerator construction is alignment of the grids relative to each other. This alignment is made in the horizontal plane (x-y direction) and in rotation about the vertical (z) axis of the accelerator.

The optical engine we have built for this purpose is shown in Figure 16. The setup consists of a precision x-y motion table with an encoder having a digital readout in the long (x) direction only. Least count of the encoder readout is 0.00004 inches

(0.001 mm). Mounted above the table is a split-image microscope with an attached TV camera and monitor. The digital readout is coupled to a programmable desk calculator having a data printout tape.

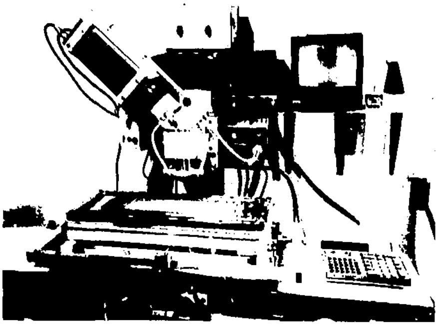

Figure 16. Optical engine with split image microscope and calculator.

Figure 17. Clean room area for arc chamber assembly.

The centerline of a grid wire is located in the x-direction (long direction) by aligning the two split images of the wire, as viewed in the monitor, until they appear as one continuous image. This x-location data point is then recorded in the calculator for each of sixty centerline positions covering approximately 25 percent of the grid area.

The calculator program then calculates and prints out the x-location of the best-fit center of the grid, the center location of each wire, the spacing between each wire, the mean spacing between wires, and the standard deviation of spacing measurements.

Once the best-fit center of each grid is measured and located, relative to the centerline of its center grid wire, the microscope is used to co-align the best-fit centers of all grids in the accelerator. The grids are then locked to the accelerator frame with mounting screws.

A typical 7 x 35 cm aperture grid is constructed with a best-fit center located within 0.001 inches (0.025 mm) or less of the center-wire centerline and will have a standard deviation of 0.0006 inches (0.015 mm) for a mean grid-wire spacing of 0.173 inches (4.39 mm) in the x-direction.

Vacuum and Hi-Pot Testing. When the arc chamber and accelerator are completed, they are assembled as a unit and vacuum tested for leaks at about 10^{-5} Torr, using a helium leak detector. If no leaks are found, hi-pot testing is performed to determine if voltage breakdown levels between grids and between electrodes and ground are within acceptable limits. Equipment for vacuum and hi-pot testing is shown in Figure 18.

Figure 18. Vacuum and hi-pot testing of a completed source.

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1. K. H. Berkner, "Manual for LBL 50-Amp Ion Beam Source," UCID 3882, (March 1974).

2. T. J. Duffy, "A 200-Amp Neutral Beam Source," Proc. of the 5th Symp. on Eng. Prob. of Fusion Research, (Princeton University, November 5-9, 1973).

Acknowledgements

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