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Development and Fabrication of New Accelerator Grid Modules for Ion Sources in the 80 keV Neutral Beam Lines for DIII-D*

H.J. Grunloh, M.G. Madruga, J.L. Busath, R.W. Callis, H.K. Chiu, M. DiMartino, R.M. Hong, R. Klasen, W.C. Martin, C.P. Moeller, H.H. Streckert, R. Tao, and P.W. Trester

General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA

***Abstract*—In 2001, efforts commenced to develop the technology to fabricate new accelerator grid modules for the ion sources in the 80 keV neutral beam lines for DIII-D. This campaign arose after water leaks began occurring with increasing frequency in the molybdenum grid rails and stainless steel water bellows of the original grid modules, fabricated in the mid-1980s. Root causes of the damage were determined and operational adjustments were made to correct the problems, but the string of failures depleted the DIII-D program of its supply of spare grid rail modules.**

The program was unable to procure new grid rail modules from any commercial source, nor was it able to obtain the molybdenum grid rails needed in two of the four module types. Efforts were then focused on fabricating new molybdenum rails required to make all four module types as well as on developing the procedures to successfully braze together the molybdenum and stainless steel parts into modules. Producing the diamond-shaped cross-section plasma grid rails proved to be very difficult, and a parallel task was initiated to design a modified source grid module that would employ circular cross-section grid rails while maintaining the most critical parameters of the original design.

The brazing development program produced procedures that yielded consistently successful brazes in all the joint types present in all the modules. The parts for new grid modules, including the new modules containing circular cross section plasma grids, were fabricated. The new brazing procedures were successfully utilized to produce four new plasma grid modules of the new design. These modules were installed in an ion source and tested to full power before being utilized in service at the end of the 2005 DIII-D experimental campaign. An overview of the ion source development program is presented and a summary of the performance of the ion source containing the new plasma grid modules is reported.

Keywords-DIII-D, neutral beams, ion source, accelerator grids, molybdenum, grid rails, brazing technology, grid rail modules, source grids, plasma grids, fabrication technology, grid rail holders

I. INTRODUCTION

This report outlines the genesis of the ion source accelerator grid fabrication program at General Atomics and describes the production and testing of a redesigned source grid layer for the DIII-D 80 keV ion sources (Fig. 1).

The neutral beam heating system of DIII-D employs eight 80 kV long pulse ion sources contained in four beam lines. Each line uses two ion sources operating in parallel to focus their beams through a common drift duct. The ion sources were designed by Lawrence Berkeley Laboratory and fabricated by RCA. The current neutral beam systems in DIII-D were completed in 1986 [1,2].

The focus of the development program described in this report is the accelerator section of the ion sources and their grid rail arrays (Fig. 2). The accelerator section extracts ions from a hydrogen or deuterium plasma generated in the arc chamber of the ion source, then focuses the ions into a beam before they are passed through a neutralizer section and a series of collimators on their path to the DIII-D vacuum vessel. The accelerator section contains four planar layers of water-cooled, molybdenum grid rails that are energized to different electrostatic potentials during operation. The precise shape and spacing of the molybdenum rails within each grid layer and between the grid layers greatly influences the performance of the neutral beams.

Figure. 1. New source grid modules using circular cross section grid rails (left) were developed to replace the original source grid modules (right), which used diamond cross section grid rails.

The successive order of the grid sections through which the ions pass, starting at the exit of the arc chamber, is source (also known as the plasma grid section), gradient, suppressor, and exit. Each section contains 4 coplanar grid modules, each

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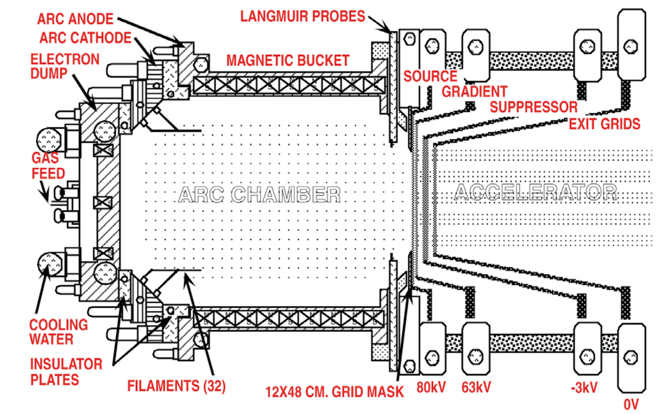

Figure 2. Schematic of DIII-D neutral beam ion source. The source grids are the accelerator grid layer adjacent to the arc chamber.

module containing 14 parallel molybdenum grid rails held in position by two stainless steel grid holders. Because of their high heat loading during operation, the rails are internally water-cooled. Water is supplied to the rails by entering a plenum in the inlet-side rail holder, passes through internal channels within the holder's finger-like structures to the rails themselves, then leaves the grid module through the fingers and plenum of the outlet-side rail holder. The molybdenum rails are fixed to the stainless steel fingers of their holders by individual brazes. The cross sectional shapes of the grid rails vary from grid layer to grid layer. The cross sectional shapes of the grids in the source, gradient, suppressor, and exit layers are symmetrical diamond, circular, elongated diamond, and circular, respectively.

Reference 3 detailed the nature and frequency of material failures that arose in the molybdenum rails after years of service that led to water leaks in numerous grid modules. Operational adjustments were made to mitigate the problems that caused the leaks, but the rash of failures depleted the program's supply of spare grid rail modules. A program was initiated to replace failed modules with new units, but no commercial source could be identified that could provide complete replacement modules nor, in particular, the symmetrical diamond cross section molybdenum rails used in the source grid modules. The program then focused efforts on internally developing the means to fabricate the diamond cross section molybdenum rails as well as the technology and procedures necessary to fabricate entire new modules.

II. DEVELOPMENT PROGRAM

The task was undertaken to develop a facility and procedure to fabricate the diamond-shaped cross section molybdenum rails for the source and suppressor modules at General Atomics. First and second generation machines were designed and built that hydraulically pulled resistively-heated molybdenum tubing of circular cross section between compressive rollers having the desired cross-sectional geometry. The second generation machine solved many of the fabrication issues that could not be rectified using the earlier machine. Reference 3 describes many of the details of the facilities. To date, a majority of the efforts to roll molybdenum grid rail stock have

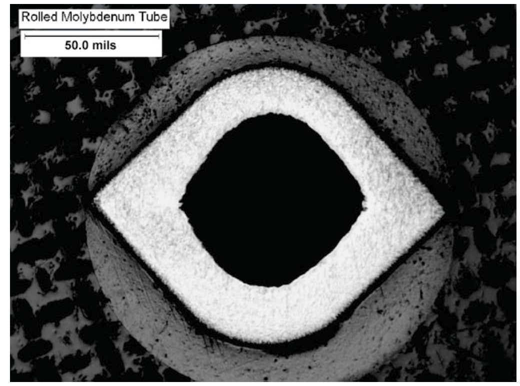

Figure 3. Photomicrograph of the cross section of a diamond shaped molybdenum source grid rail produced in the new grid rail fabricating machine.

focused on the production of source grid rails. Excellent cross sectional geometry has been attained (Fig. 3), yet the consistency of the cross section and the straightness of the rails have not yet reached production quality. Efforts to reach this quality level will continue in the future.

An internal program was conducted to develop the hardware and techniques necessary to successfully and consistently yield high quality brazes in the joints of the grid modules. Early attempts to produce the braze joints focused on repairing ex-service grid modules. Since service failures occurred in either the molybdenum rails or, in the case of the source modules, the thin-walled stainless steel bellows that delivered water from the plenum in the base of the holders to the tips of the rail support fingers, repair brazes were conducted exclusively on the joints connecting new molybdenum rails to ex-service stainless steel holders or new stainless steel bellows to ex-service stainless steel holders. It proved to be difficult to achieve successful brazes in either of these joint types. Successful brazes were finally achieved in these repair situations when appropriate cleaning steps were incorporated.

Lessons learned from the repair braze program were utilized to successfully complete the development program for fabricating new modules. Early tests of brazes on new molybdenum rails and new stainless steel holder specimens suffered many of the same problems that were encountered making repair brazes.

The braze development program eventually produced consistently successful brazes in the molybdenum rail to stainless steel holder joints, the stainless steel bellows to stainless steel holder joints, and the stainless steel plenum cover plate to stainless steel holder joints. Fig. 4 shows a molybdenum suppressor rail to stainless steel holder braze produced by the development program.

The difficulties encountered in producing the diamond cross section source grid rails by the hot rolling method gave rise to a parallel effort to design a modified source grid module that used circular cross section rails while maintaining the most critical parameters of the original design. The advantage of the new module would be purely manufacturability as sources for circular cross section molybdenum tubing are plentiful. Success

Figure 4. Successful test braze of a molybdenum suppressor rail to a stainless steel holder specimen.

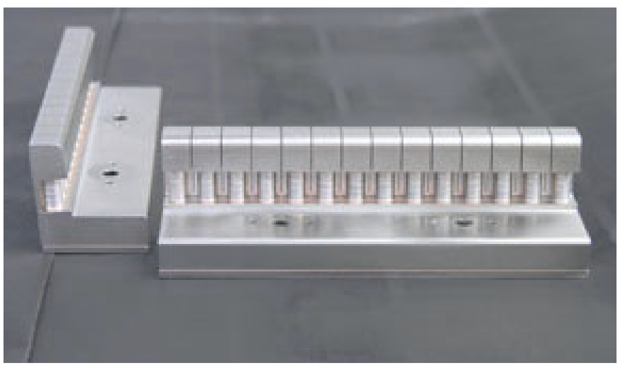

Figure 5. Completed source grid rail holders after successful bellows and plenum cover plate brazes.

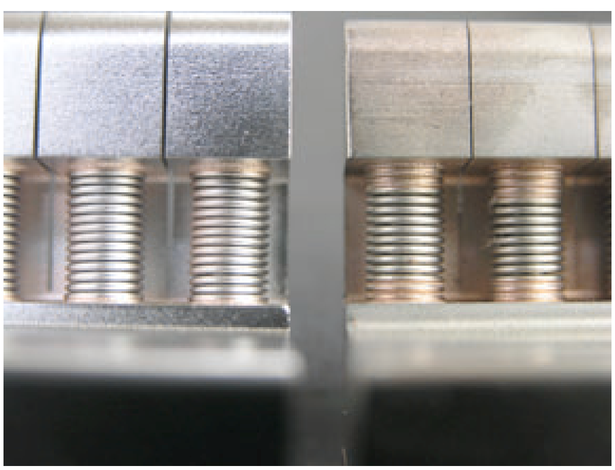

Figure 6. Comparison of new source module bellows brazes (left) with original RCA bellows brazes (right). Superior control of braze metal in the new module fabrication eliminates wetting of braze metal onto bellows convolutions.

in the development of a new source module would be achieved if the performance parameters of the original ion source with diamond shaped source grid rails could be attained or nearly attained by an ion source employing circular shaped source grid rails. Details of the technical justification of the new design and the operational testing of the resulting ion source are given in [4].

III. MODULE FABRICATION

The stainless steel grid rail holders used in the modified source modules were simpler to fabricate than the holders for the diamond cross section rails. Sufficient holders, plenum cover plates, bellows, and circular cross section molybdenum rails were fabricated to produce the four modified source modules needed to outfit one ion source. Special braze fixtures developed in the test program were used throughout the module fabrication process.

Excellent brazing results were achieved in all braze cycles as all holder assemblies were fabricated without a braze leak (Fig. 5). Comparing the bellows brazes achieved in the current production run with those of the original RCA module fabrication, Fig. 6 shows the advantages of tighter braze material control in the current brazes (left) over the originals (right) as the RCA brazes froze multiple bellows convolutions at each joint while no convolutions were frozen in any bellows during any of the current holder fabrications.

After a final machining operation on the plenum covers to attain final precise dimensions on the holder assemblies and helium leak testing on all holders, preparations began on the molybdenum rail to stainless steel holder brazes. Modifications were made to the original braze fixtures to tighten important tolerances and to add features to incorporate multiple furnace thermocouples and improve rail fixturing. All pre-braze procedures followed the standards developed in the test program. The fixtured modules were dimensionally inspected prior to loading into the vacuum furnace to assure dimensional precision. The production runs for the molybdenum rail to holder brazes were all successful; all joints were well wetted and all exhibited structurally robust braze fillets (Fig. 7).

Figure 7. Newly fabricated source module showing successful molybdenum rail brazes (top), bellows brazes (middle), and plenum cover plate braze (bottom).

IV. INSPECTION AND ASSEMBLY

Only one leak was identified in post-braze helium leak testing of the four new source modules. The leak was found to be caused by a micro-pore in the stainless steel base metal in one of the rail holders. The leak, which had not been detected after the holder assembly braze cycle, was found after the module assembly braze run. This leak was successfully repaired by micro-TIG welding.

Flow tests were performed on all completed modules to assure that no interior flow blockages had been formed during brazing. Using an IR camera, each module was viewed while alternating flows of cold and hot water were run through from inlet to outlet plenums. All rails in all modules showed uniform thermal response to changes in water temperature, indicating no blockages existed (Fig. 8).

The four new modules were individually inspected for dimensional accuracy. All critical dimensions were found to be within the ± 0.002 in. (0.050 mm) specified tolerance range.

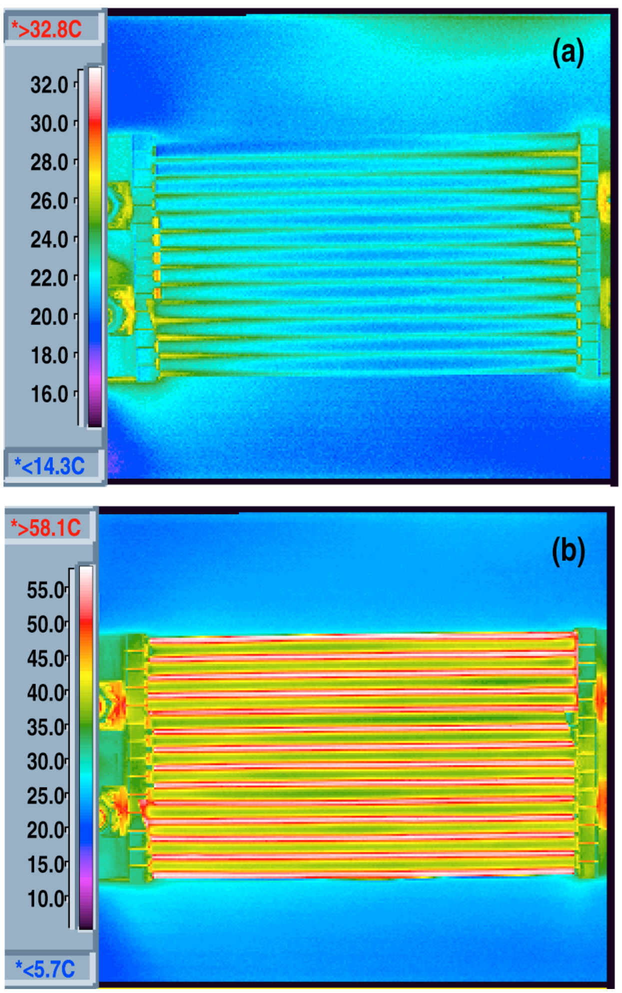

Figure 8. Infrared photographs of newly completed grid module undergoing internal flow tests. Uniform temperatures of rails under (a) cold water flow and (b) hot water flow indicate no internal flow obstuctions.

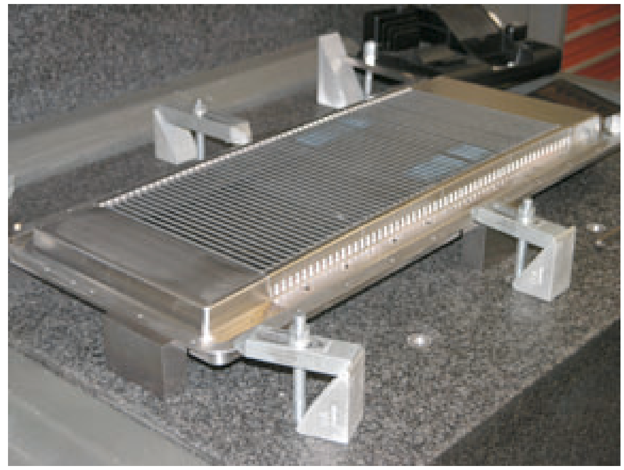

Figure 9. Newly completed source grid modules assembled into the source grid hat assembly undergoing dimensional inspection on a Cordax coordinate measuring machine.

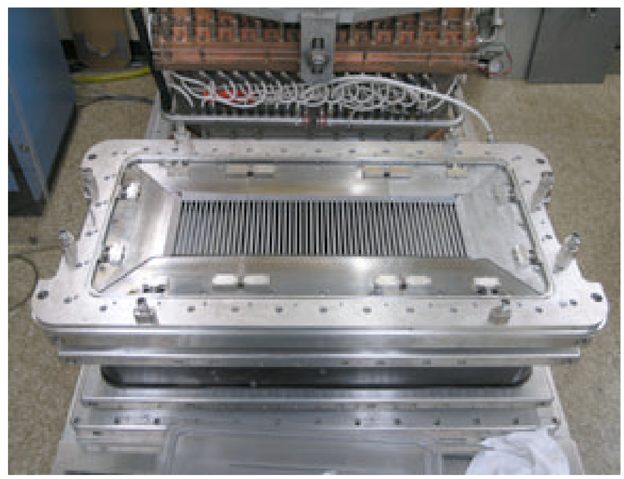

Figure 10. Assembled ion source accelerator section displaying newly fabricated source grid modules below masking plate framework.

The modules were then assembled in the source module hat assembly. This assembly was then inspected on a Cordax coordinate measuring machine (Fig. 9) and again, all critical dimensions were found to be within the ± 0.002 in. (0.050 mm) tolerance range. The accelerator section of the ion source was then rebuilt using the new source module hat assembly and a modified masking plate to compensate for the added height of the modified source modules (Fig. 10). Completion of the ion source reassembly followed standard procedures.

IV. INSTALLATION AND PERFORMANCE TESTING

The modified ion source was reinstalled into the 210-deg neutral beam line in DIII-D (Fig. 11). A week of conditioning and performance testing of the new source was then initiated. Reference 4 details the performance characteristics achieved by the modified source. Results showed the ion source performed comparably to the original ion source, with only a 4% loss of

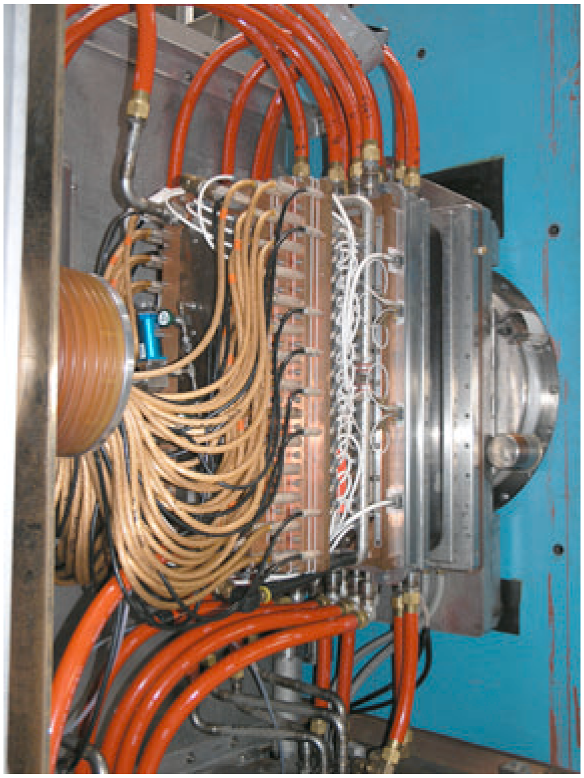

Figure 11. Newly modified ion source reinstalled in 210-deg neutral beam line of DIII-D awaiting conditioning and performance testing.

beam power produced. Other operational parameters were also found to be well within reasonable operational ranges. The 210-deg neutral beam line was returned to service and operated without incident for one month to the end of the 2005 DIII-D physics campaign.

CONCLUSION

Producing comparable performance to the original design, the modified ion source has been deemed a success. The technology and procedures needed to fabricate all new grid modules for all four sections of the ion source accelerator for DIII-D have now been developed. The lifetime of these sources can now be greatly extended for many years to support fusion science and energy research. This technology can also be readily applied to the manufacturing of ion sources for other fusion research facilities internationally.

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