Indigenous Manufacturing realization of TWIN Source

R. Pandey1, M. Bandopadhyay2, D. Parmar2, R. Yadav2, H. Tyagi2, J. Soni1, H. Shishangiya2, D. Sudhir Kumar2, S. Shah2, G. Bansal1, K. Pandya1, K. Parmar1, M. Vuppugalla1, A. Gahlaut1 and A. Chakraborty1

1Institute for Plasma Research, Nr. Indira Bridge, Bhat, Gandhinagar-382428, India
2ITER-India, Institute for Plasma Research, Bhat-Motera Road, Ahmedabad - 380005, India
3Homi Bhabha National Institute (HBNI), Anushaktinagar, Mumbai- 400094, India

E-mail: rpandey@ipr.res.in

Abstract. TWIN source is two RF driver based negative ion source that has been planned to bridge the gap between single driver based ROBIN source (currently operational) and eight river based DNB source (to be operated under IN-TF test facility). TWIN source experiments have been planned at IPR keeping the objective of long term domestic fusion programme to gain operational experiences on vacuum immersed multi driver RF based negative ion source. High vacuum compatible components of twin source are designed at IPR keeping an aim on indigenous built in attempt. These components of TWIN source are mainly stainless steel and OFC-Cu. Being high heat flux receiving components, one of the major functional requirements is continuous heat removal via water as cooling medium. Hence for the purpose stainless steel parts are provided with externally milled cooling lines and that shall be covered with a layer of OFC-cu which would be on the receiving side of high heat flux. Manufacturability of twin source components requires joining of these dissimilar materials via process like electrode position, electron beam welding and vacuum brazing. Any of these manufacturing processes shall give a vacuum tight joint having proper joint strength at operating temperature and pressure. Taking the indigenous development effort vacuum brazing (in non-nuclear environment) has been opted for joining of dissimilar materials of twin source being one of the most reliable joining techniques and commercially feasible across the suppliers of country. Manufacturing design improvisation for the components has been done to suit the vacuum brazing process requirement and to ease some of the machining without compromising over the functional and operational requirements. This paper illustrates the details on the indigenous development effort, design improvisation to suit manufacturability, vacuum brazing basics and its procedures for twin source components.

1. Introduction

Large area multi driver inductively coupled RF negative ion sources have emerged as the baseline option for multi megawatt neutral beam injectors required for fusion applications [1]. RF based negative ion source couples RF power produced via RF generator for plasma production in driver region which expands in plasma box region and further negative ion beams are extracted via multi apertures grid segments. Such a RF based negative ion source consisting of two driver is defined here as TWIN source. The experimental objectives, conceptual design of TWIN source experiment have already been reported [3]. TWIN source would consist of two driver sub-assemblies and a plasma box.
sub-assembly during plasma Phase of experiment and later on it would be supplemented by grid sub-
assemblies during extraction phase of experiment. The two drivers of TWIN source would be coupled
with a RF power of 180 kW. Source would be operated in continuous mode for 5 s and for 5 cycles
with 5 Hz modulation for ~ 3 s ON 20 s OFF. As the components of various sub-assemblies of TWIN
source would be receiving the heat flux, the engineering design of these components has been done
accordingly to keep the thermo-mechanical stresses well within limit. Material selection of these
components require high vacuum compatibility and strength at elevated temperature. SS 304L grade of
stainless steel material are selected to provide structural integrity at elevated temperature and vacuum
compatibility whereas OFC-Cu (UNS –C 10100) grade of copper has been selected for the plasma
facing side being high on thermal conductivity value and with good brazing properties. These
components are actively cooled via water as cooling medium. Major manufacturing requirements of
these component are machining of complex cooling path over stainless steel material and covering
these cooling paths with a copper layer. In the earlier manufacturing of similar kind of ion sources
non-conventional processes like Copper electrode position has been opted. Taking the indigenous
manufacturing attempt the readily available manufacturing process like Vacuum Brazing has been
selected for joining of dissimilar materials. Thus the baseline engineering design has been revaluated
and modified accordingly to accommodate the application of vacuum brazing process. In the following
sections details on such design modification and glimpse of manufacturing activities have been
provided.

2. Design and Engineering of TWIN source Components

Approach for engineering design on twin source mechanical components is three steps procedures as
highlighted in figure 1. It includes pre-engineering conceptualization, detailed engineering design and
design re-assessment steps. At pre-engineering steps several functional and operational parameters of
twin source is generated. These parameters will be the design basis for detailed engineering of the twin
source components that shall include overall dimensioning, thickness optimization as per applicable
design code and standard engineering practices. A conceptual model is thus prepared using CAD that
shall visualize these parameters, geometrical, space constraints and several interfaces with auxiliary
components. At third step inputs from suppliers has been taken for the indigenous manufacturing
realization of twin source. Based on the inputs few design improvisation done to accommodate the
commercial availability of manufacturing techniques across country. These details are listed in
following sub-sections.

![Figure 1. Design Route for TWIN source Components](image)

2.1. Detailed Engineering design with manufacturing assessment

The source of weight ~ 2 tons is mounted in a cantilever position, placed between two vacuum vessels
and supported by the vacuum vessels’ flanges through a thick (~ 40 mm) stainless steel collar flange,
as shown in figure 2. The source and the collar flange are interfaced through a thick vacuum
compatible fiber reinforced polymer (FRP) ring structure to maintain the high voltage isolation
between the source and the chamber as shown in figure 3.
Complete assembly of ion source basically consists of plasma box sub-assembly (figure 4) and driver sub-assembly (figure 5). Plasma box assembly holds the plasma box lateral wall (1000 × 500 × 200 mm³) with end flanges holding source back plate. Whereas driver sub-assembly consist of faraday screen lateral wall, faraday screen back plate and alumina case housing the entire driver assembly. The two drivers are mounted over plasma box source plate through four number of supporting rods (for each driver). Drivers form a vacuum sealing over source back plate with O-ring mechanism and are electrically isolated with source back plate. Each drive assembly and plasma box assembly has separate cooling paths.

**Plasma chamber lateral wall:** It is a rectangular shape box structure as shown in figure 4, whose one side is covered by RF driver holding back plate and the other side will be covered by plasma grid (PG) – bias plate combination. The size of the structure is ~ 1000 (L) × 500 (B) × 200 (H) mm³. The base material is SS 304 of thickness 6 mm. Milled cooling lines are provided in the lateral wall on the base material. The inner side walls are provided with OFC-Cu layer to distribute the heat load due to plasma loading uniformly over the whole surface. **Source back plate:** It holds both the RF drivers in horizontally demountable configuration. The size of the plate structure is ~ 1000 × 500 mm² of thickness 30 mm. The base material is SS 304L. Cooling lines are milled on the back side of SS plate on plasma facing side, which shall be covered with 5 mm thick copper layer.

**Driver:** Driver assembly comprises of many components, whose exploded view is shown in figure 5. The outer most component is a ceramic (Alumina) cylinder of grade A6 – A9, diameter 280 mm, length 150 mm, thickness 8 mm. The ceramic cylinder (CS) acts as a vacuum boundary for RF window which will house the Faraday shield (FS). RF helical coil antenna will be mounted on the CS. FS consists of few different parts. FS is placed inside the CS to protect the CS from plasma sputtering and is coated with 3 micron Molybdenum from inside. The whole OFC Cu cup is then mechanically coupled with a SS 304 plate (Driver magnet plate) which houses Samarium Cobalt magnets in the other side (rear side). Magnets are placed in chequer board configuration inside the channels milled on the rear side of the SS plate in matrix formation. To protect magnets from fly-off, all the magnets are mechanically covered with a SS thin plate. The whole driver back plate, few opening are provided to hold starter filament, windows for diagnostics, gas feed nozzle, Cesium injection nozzle etc. The
vacuum tightness between the CS and the FS is ensured by an O-ring pressed by Driver cover plate, made of SS 304L of thickness 26 mm and of diameter 300 mm.

2.2. Design re-assessment based on manufacturing input
Based on feasibility study and inputs from various manufacturers, engineering design of few components were re-assessed and some modifications done to suit with the manufacturing requirement and ease of the process. **Plasma box lateral wall:** Plasma box lateral wall is split in to four segments and on each segments cooling lines are provided by external milling on the stainless steel part (figure 6). The earlier concept of having deep drilled cooling lines running parallel across length of lateral wall is converted in to rectangular slots with same hydraulic radius. Difficulties pointed by in deep drilling 150 mm straight path with conventional processes thus resolved by application of vacuum brazing process, by which the externally milled cooling slots would be covered with 1mm thin OFC-Cu sheet by surface to surface bonding.

**Figure 6.** Plasma box lateral wall with milled rectangular slots externally

**Faraday shield Lateral wall:** Very significant modification done for faraday shield lateral wall, where the Z-slot configuration (figure 7) achieved with a proposal to split the design in two parts i.e. inner and outer cylinders. Inner cylinder will be manufactured with L-slot configuration on lateral surface and outer cylinder will have straight I-slot. Then these two parts would be vacuum brazed with surface to surface bonding by adjusting the L-slot and I-slot configuration in a manner that final assembly yields a z-cross section in the lateral wall.

**Faraday shield back plate:** Similarly for faraday shield back plate the requirement of a 10 mm thick copper plate (figure 8) having cooling channels embedded inside, is achieved by splitting the assembly into two parts. One having 6.5 mm thickness with 3.5 mm deep cooling lines milled externally on it, whereas the second part having 3 mm thickness is vacuum brazed to it.

**Figure 7.** Z-Slot configuration of FS wall

**Figure 8.** FS back plate assembly

2.3. Finite element analysis for components
Several finite element analyses have been carried out to estimate the structural integrity and thermal response of the individual sub-assemblies. Maximum stress is limited up to 115 MPa and deflection is limited to 1 mm only.
3. Manufacturing development of TWIN source experiments

3.1. Vacuum brazing for TWIN source components

Vacuum brazing being one of the most reliable techniques of joining dissimilar materials for vacuum tight joint, the same has been opted for twin source components for joining Stainless steel and OFC-Cu. The major challenge in this was with the larger dimensions of components, the required clearance gap of 100 microns between the mating parts is never assured despite best machining practices. Hence, a lot of trials have been done with fixture design to assure this minimum gap clearance. The brazing filler alloy mostly used is Bv Ag-8 (Cu-Sil alloy), while in some places Bv Ag-29 is also tried to ensure greater fluidity based on geometrical consideration. SS part is Ni plated to increase the fluidity of molten braze alloy thus by giving a vacuum tight joint reasonably high on strength. Prior to brazing SS part was chemically cleaned in solution of 20% sulphuric acid + 20% hydrochloric acid + 60% water followed by a dip in to 10 % nitric acid. OFC-Cu part was also chemically clean to remove all oxide and surface impurities in a solution of 25 % sulphuric acid + 10 % potassium dichromate followed by rinsing in hot water. The temperature for stabilizing is kept as 650 °C and that for brazing as 850 °C for a soak period of 10-20 min each. The heating rate was kept at 9 degree/min. The vacuum furnace was maintained at vacuum level of 10⁻⁵ mbar using a diffusion pumping system. Before the final run a sample run for Cu-Cu joint and SS-Cu joint was done under same condition. The test coupons then sent for tensile testing and macroscopic examination. Macroscopic results gives a fine eutectic mixture of brazing alloy where as in tensile testing failure occurs at parent material denoting strength more than 200 MPa.

![Figure 9. Plasma Box Assembly](image1)

![Figure 10. Faraday Shield Assembly](image2)

Manufacturing of plasma box assembly (figure 9) has been achieved with End flanges TIG welded to SS part of plasma box lateral wall. Manufacturing realization for the source back plate done by milling cooling lines over stainless steel part externally and then covering it with another copper sheet of 5 mm thickness through vacuum brazing process. 3 microns of Mo coating achieved by DC magnetron sputtering unit. The manufacturing realization of faraday shield lateral wall (figure 10) assembly achieved with combination of two sets of concentric cylinders made of OFC copper. The inner cylinder has the L-slot configuration and the outer cylinder has the straight I-slot configuration. Later on these two would be vacuum brazed keeping orientation of L-slot and I-slot in such a manner that the final assembly of FS lateral wall achieved the Z-slot configuration. Once the lateral wall assembly is achieved the faraday shield back plate assembly with SS cooling tubes is achieved with vacuum brazing option. Plasma grid segment (figure 11) is made of stainless steel whereas bias plate is made of OFHC copper. Both the components are required to have frame cooling. For both the components the cooling lines are attached with vacuum brazing post all the milling operations are finished on individual components. B Ni-3 brazing alloy is used for plasma grid segment (SS-SS joint) and Bv-Ag-8 braze alloy for bias plate assembly (Cu-Cu).
3.2. Testing of brazed components

All the brazed components passed the leak tightness test up to level of $\sim 10^{-9}$ mbar l/s. The leak testing was carried out by evacuating the cooling channels below vacuum level less than $10^{-3}$ mbar and then spraying helium gas all around the brazing joints (figure 12). The cooling lines were further pressurized to high pressure up to $\sim 10$ bar with demineralized water for 30 min. The voltage isolation test where performed over insulating parts using 2.5 kV AC supply and 5 kV DC supply. The IR resistance measured over more than 100 M$\Omega$.

4. Conclusion

This indigenous manufacturing realization of twin source components has established the economical way of manufacturing such a large dimension ion source without compromising over its functionality. Learning experiences with the application of vacuum brazing process over such larger dimension components, issues with gap clearance of the mating parts and the need of design improvisation for components and fixtures to improve the capillarity of molten filler alloy were quite significant. Such lessons could be a part of standard vacuum brazing practices for future application.

Acknowledgement

Authors have acknowledged the contribution of M/S Design-Tech personnel for CAD modeling and M/S Hind High Vacuum, Bangalore for manufacturing the TWIN source components.

References

[1] Marcuzzia D, Dalla Palma M, Pavei M, Heinemann B, Kraus W, Riedl R 2009, Fusion Engineering and Design 84 1253.

[2] Singh M J, Bandyopadhyay M, Bansal G, Gahlaut A, Soni J, Sunil Kumar, Pandya K, Parmar K G, Sonara J, Yadava R, Chakraborty A K (IPR, India), Kraus W, Heinemann B, Riedl R, Obermayer S, Martens C, Franzen P, Fantz U (IPP, Germany) 2012, AIP Conf. Proc. 1390 604.

[3] Bandyopadhyay M, Pandey R, Shah S, Bansal G, Parmar D, Gahlaut A, Soni J, Yadav R K, Sudhir D, Tyagi H, Pandya K, Parmar K G, Mistri H S, Vuppugalla M and Chakraborty A K, 2014 IEEE Transactions on Plasma Science 42 624.