TECHNOLOGIES FOR REALIZATION OF LARGE SIZE RF SOURCES FOR –VE NEUTRAL BEAM SYSTEMS FOR ITER
Challenges, experience and path ahead

Jaydeep Joshi[1,2], Arun Chakraborty[1], Hitesh Patel[1], M.J, Singh[1], Mainak Bandyopadhyay[1,2]
[1]ITER-India, Institute for Plasma Research
Gandhinagar, India
[2]HBNI Training school complex
Mumbai, India
Email: jaydeep.joshi@iter-india.org

Eberhard Pfaff[3], Jörg Schäfer[3], Christian Eckardt[3]
[3]PVA Industrial Vacuum Systems GmbH
Wettenberg , Germany

Aron Metz[4], Marko Gelfert[4]
[4]RI Research Instruments GmbH
Bergisch Gladbach, Germany

Abstract

Technologies for manufacturing of small and medium size Ion source (upto four RF driver) for positive and negative neutral beam systems have been evolved over last many decades and such ion sources are being successfully operated at various experimental facilities across the world. However, as the need arises for the larger size ion sources (eight driver) for ITER diagnostics and heating neutral beam systems, several existing manufacturing technologies and considerations have to be upgraded and re-evaluated to qualify them for (1) highest vacuum quality class (2) nuclear environment. Diagnostic Neutral Beam (DNB) source is the first candidate in a family of such big size ion sources, being manufactured according to the ITER specification with 're-evaluated' manufacturing technologies and it throws light on many unforeseen challenges as manufacturing progresses. The nature of challenges are mainly related to usage of the material with radioprotection requirement, special requirements on weld joint configuration to enable full penetration with 100% volumetric inspectability, dissimilar material welding technologies, machining process development to meet stringent dimensional accuracies (in the range of 10-50 microns) of individual 'angled' grid segment to achieve overall alignment of +/-0.2mm, electro-deposition of copper with thickness>3mm over the angled surfaces with control over distortion, development of post insulators with threaded connection between metal and alumina, with load carrying capacity of 10kN and electrical isolation of 140kV in vacuum. The paper describes the experience gathered in development of above mentioned manufacturing technologies, the methodology adopted for mitigating the practical limitations, prototyping to establish and qualify the manufacturing procedure, evaluating the non-conformities, assessment of deviation proposals, in compliance with ITER requirements.

1. INTRODUCTION

Beam source for ITER Diagnostic beam is designed to produce a 100keV, 60A, 60MW Hydrogen beam, for measuring the Helium ash content in the Deuterium–Tritium (D-T) phase of the ITER machine using the Charge Exchange Recombination Spectroscopy (CXRS) [1, 2]. The design, to achieve this, essentially consist of 8 driver based Cesiated RF ion source with an extraction plane of 1.8 m x 0.6 m coupled to a 100 keV extractor and accelerator system. The duty cycle for beam extraction and acceleration is 3 sec ON/20 sec OFF with 5 Hz modulation during the ON period. Fig. 1 shows the accelerator and ion source configuration.

Main components of ion source consist of the actively cooled components like (1) 4 Nos. of water cooled L shaped Plasma Box lateral walls (2) Faraday shields and driver back plate (3) 4 Nos. of water cooled Plasma driver plate. These components are structurally supported on a 20mm thick SS304L Rear Driver Plate. These components are shown in Fig. 1. The accelerator essentially a multi aperture grid system, consist of three grids namely, Plasma grid (PG), Extractor grid (EG), Grounded grid (GG) as shown in Fig 2. Each grid consists of 4 segments with 1280 apertures in total. One segment of the grid has 4 beam groups, each carries 80 apertures in a 5 x 16 pattern [3]. The 4 segments of a given grid are mounted on a support frame which in turn are connected with the grid mounting flange. Different grid systems have been separated electrically through alumina post insulators. Beam optics for this accelerator system is designed to transmit high current, low divergence beam over a long distance (~20.67m) through a narrow aperture on ITER blanket [1, 2]

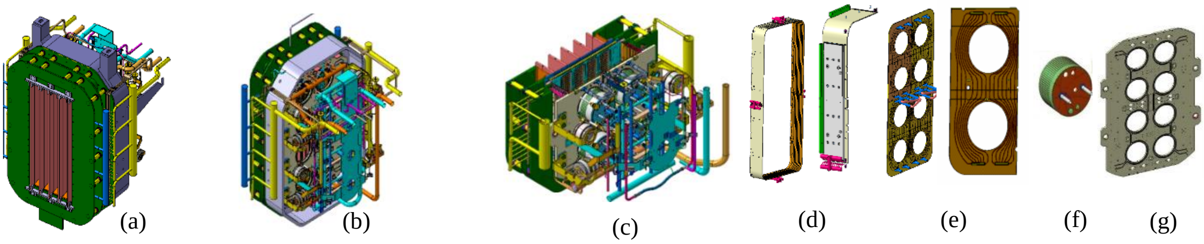

FIG. 1. (a) Accelerator with size of 1.4m x 2.2m x 0.4m (b) Ion source with size of 1.5m x 1.9m x 1.1m (c) Cross section throigh Beam source (d) 'L' shaped lateralwalls (e) Plasma driver plate (f) Faraday shield (g) Rear driver plate .

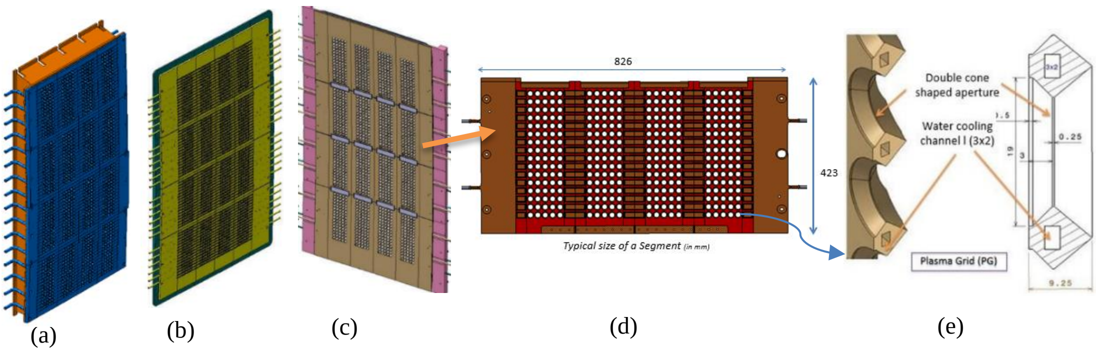

FIG. 2. (a) Grounded Grid (b) Extractor grid (c) Plasma grid (d) typical segment of a Plasma grid (e) configuratino of an aperture of plasma grid segment.

This configuration of Ion source and accelerator is aimed to (i) Produce uniform plasma density over the extraction area of 1.8m (h) x 0.6m (w) (ii) Extract the current densities to the tune of 34 mA/cm2 (iii) Accelerate of the beamlets to 100kV (iv) Transport the beam upto the focal point located at the distance of 20.665 m from the downstream of grounded grid [3]. The achievability of these aim is largely dependent on the manufacturing design of the above sub components, and the key aspects of this manufacturing are: (1) realization of angled grid segments with the stringent manufacturing tolerances on the aperture positioning, flatness and angles, which are derived from the functional requirements to have the aperture to aperture positioning of +/-0.2mm in the assembled condition (2) design of weld joint geometry to enable the full penetration weld with 100% volumetrically inspectable, which is mandatory requirement for all the water to vacuum boundary connections (3) design of alumina insulators with internal threads for bolted connection with metallic flanges, to provide the mechanical connection between grid mounting flanges and electrical isolation upto 90kV (4) Material selection and procurement with the restricted chemical composition of Cobalt (Co), Niobium (Nb) and Tantalum (Ta) for adaptability to ITER's radiative environment (5) Handling of Deviation and Non-conformities.

The following sections of the paper shall describe route through which the above manufacturing design has been realized along with the challenges faced during the course, their solution adopted and the results. Other than the core technological discussions, an additional section has also been incorporated to highlight some important examples of handling the non-conformities which occurred during the manufacturing and deviations, along with the approach to technically comply with the system requirements.

2. GRID SEGMENT MANUFACTURING

From the precision point of view, the accelerator of beam source is the most complex element of neutral beam system, which is composed of a multi-aperture grid system with three water cooled grids made from Oxygen free Copper according to EN 13599 [4]. Focussing of the beamlets to a point located at 20.665 m from the grounded grid is obtained using a combination of segment bending and aperture offsets. To achieve this focusing requirement, the grid segments are designed with two stage angles (0.222º and 0.665º) from the centerline in the horizontal direction as shown in Fig. 3. Transporting maximum beam current over 20.665 m demands a stringent control on beam optics which in turn requires a control on the dimensions of flatness, angle and aperture positioning. Before manufacturing, the target considered for these dimensions were: (i) flatness: 40microns (ii) angle tolerances: +/− 0.002 Deg (iii) aperture positioning: 50 microns. However, grid segments in angled form with such tight tolerances has never been built and therefore, to understand the feasibility of achievability of these tolerances and to unveil the challenges related to this, prototyping route was adopted, where 1:1 size segment was manufactured for the most complex type of grid i.e Plasma Grid.

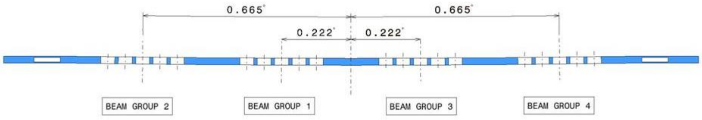

FIG. 3. Bending angles in horizontal direction of the beam groups for a given segment[5]

2.1. Prototype grid segment development

During the prototype manufacturing, it was experienced that the material condition plays a vital role in achieving the initial level of flatness. Use of forged material with the yield strength of 240 MPa (i.e EN 13599 Grade R240) provided the good combination of machinability and the flatness control upto the level of 2.4mm at the first stage of machining on flat plate. In addition, the internal stresses caused by extensive machining operation has to be released after each major machining operation and therefore it is essential to incorporate the intermediate stage of annealing at 180 C. To note, this annealing operation has minor impact on the grain size (grain size at 140 C: 70microns, grain size at 180 C: 120microns), however the material tensile strength stays unaffected and therefore, the higher temperature could be adopted to release the stresses to the extent possible.

Due to the angled surfaces, customized machining fixtures have been designed to enable the machining from both surfaces. For the machining at side 1, where the apertures are not drilled, a vacuum clamping fixture has been used to provide the uniform clamping force over the complete surface. At the second stage, where the vacuum clamping could not be used due to already drilled apertures, a mechanical fixture with the top cover plate has been used. It is important to note that accuracy of the base plate after removal from the fixture is largely dependent on the fixture clamping surfaces which implies that these surfaces must be generated and retained with the accuracy as high as desired from the base plate. A typical fixture is presented in Fig. 4.

Copper electrodeposition of the min. thickness of 3mm over the surface of ~0.8m x 0.45m with varying angles required the tight control of bath parameters (temperature, current flow and its direction, voltage), to control the process induced internal stresses. Manufacturer’s skill and experience on the bath chemistry control, deposition rate, balancing the stress direction with respect to angle of surface and stress releasing could help in achieving the flat surfaces.

Post manufacturing electro-polishing is the conventional route being adopted for achieving the surface finish. However, the measurement of aperture diameter showed that the material removal during this process resulted in the diameter deviation in >80% apertures, which were within the tolerance before the electropolishing. Therefore, the process of electro-polishing was replaced with mechanical polishing using a diamond based tool to achieve the desired surface finish of 0.8μRa on the aperture surfaces.

The measurements of angle, flatness and aperture coordinates has been carried out by one of the most sophisticated Coordinate Measuring Machine (CMM) with accuracy of 2-3 microns. However, due to the configuration of aperture, there is limited space available on the top surface of plate to deploy the CMM probe. Therefore, alternative surfaces at the central cylinder of aperture have been used, where a cylindrical probe could be used for the coordinate measurement.

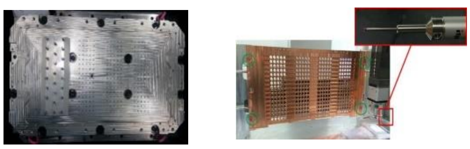

FIG. 4. (a) Machining fixture (b) Dimensional measuremet of a segment, mounted vertically on CMM

To understand, how the segment retains the achieved dimensions during the handling and storage, various exercises for have been performed and measurements have been carried out and compared. These include, the vertical storage, horizontal storage for the period varying from few hours (~4-5 Hours) to few days (~3 days) and handling in horizontal condition. The outcome showed that the horizontal handling and storage changes the dimensions (mainly angle) drastically (deviation ~0.024 Deg) and therefore not recommended to handle the segment in horizontal condition once the all operations are completed.

2.1.1. Learnings from the prototype grid segment

Development of prototype grid segment has established a complete route of manufacturing an angled segment along with the measurement technique. Number of recommendations have emerged out of this manufacturing, which are mainly (1) the use of half hard material with the strength of R240 and forged plate (2) temperature synchronization between the machining room and measurement area (3) improvisation of vacuum clamping fixtures by incorporating the additional mechanical clamping, to avoid the possible slippage of plate over the fixture due to machining forces (4) intermediate measurements and correction of clamping tool (5) handling in vertical condition during all the stages after final machining (6) replace electro-polishing with mechanical polishing to achieve the surface finish (7) improvisation in the electrodeposition parameters to control the internal stresses(8) apply the ‘best fit’ technique and drill the final diameter of reference hole at a position that it places all the apertures in the tolerance band.

2.2. Production of ‘angled’ segment- Plasma grid

With incorporating the recommendations from the prototype grid segment, the production of first lot of segments for Plasma Grid (3 Nos.) has been completed. Photograph of one such segment is shown in Fig. 6.

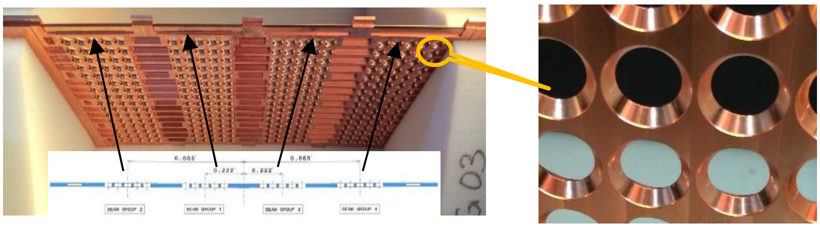

FIG. 6. Production of Plasma Grid segment (showing the angled configuration) and the apertures

The summary of worst dimensional accuracies achieved are as presented in Table 1. A comparison is also made with the accuracies achieved during the prototyping phase to show how the incorporation of prototyping experience effectively improves the final product.

TABLE 1. ANGLES, FLATNESS AND APERTURE POSITIONS

	Beam group angles (Deg)				Beam group plane flatness (microns)				Aperture position (microns)			
	BG 1	BG 2	BG 3	BG 4	BG 1	BG 2	BG 3	BG 4	BG 1	BG 2	BG 3	BG 4
Nominal Value	0.665	0.222	0.222	0.665	0				0			
Targeted Tolerance	+/- 0.002	+/- 0.002	+/- 0.002	+/- 0.002	40				50			
Deviation- Segment 2	0.014	-0.005	-0.015	-0.006	40	108	116	37	68	69	49	44
Deviation- Segment 3	-0.003	0.010	-0.003	-0.011	197	136	86	116	21	23	25	38
Deviation- Segment 4	-0.006	0.007	-0.005	0.003	206	163	133	159	22	24	33	43
Prototype Grid	-0.072	0.031	-0.014	-0.091	0.166	106	81	75	42	35	67	96

Apart from learning from prototype grid segments, it is important to note few important parameters emerged during the production cycles. These are: (1) Series of controlled straightening by experienced hands is necessary to be performed after manufacturing for the individual beam group such that correction of one beam group does not impact the adjacent one. Further, the angle and flatness are interlinked parameters and therefore, it is essential to monitor both parameter simultaneously during the straightening exercise. (2) Electro-deposition on the 'angled' segment for a thickness as high as 3mm requires special bath parameter control. The high residual stresses introduce the deformation in the segment of 10mm which is corrected by annealing followed by straightening to the desired dimensions. This deformation is dependent on the direction of residual stresses. To mitigate the risk a strip based technique has been adopted where, before initiation of electrodeposition on the production plate, a thin strip (thickness ~0.2-0.4mm) with a soft material is put into the bath and thin layer of deposit is applied on it. The direction of bending of thin strip provides the guideline on the behavior of electrolyte bath and thereby iterations on the parameters could be made to achieve the desired direction of stresses. (3) No matter how strict control is adopted, with the most sophisticated manufacturing techniques, there is always a possibility that the micro level variation in the material metallurgy and structures would lead to different behavior of different segment (though made from the same heat) and the exact replication of results is not possible. Each production cycle is a new experience and corrective measures, if required, have to be applied accordingly.

3. WELDING TECHNOLOGIES AND RELATED ISSUES

The hydraulic interface of the actively cooled components, which is in form of welded connection, is the most sensitive area prone to failure during operation. Additionally, for the water to vacuum boundary connection within the neutral beam vessel (i.e VQC1A from ITER environment perspective), this welded connection has to be full penetration butt weld with the 100% volumetric inspectability. To fulfil these requirements, extensive manufacturing design[1] (in terms of joint geometry, welding process selection, manufacturing sequence, pre-post processing, tolerances) has been performed for the connection of hydraulic line to grid base plate. This design includes a 'U' shaped copper stub, which is set-up with the base pate with tight fit-up tolerances, and thereby it forms the square butt weld edge of thickness ~15mm. The electron beam enters to the base plate from the top and penetrates upto the thickness upto 17mm. The root of the weld is dumped into the removable baking strip, which avoids the possibilities of 'root pore' into the base material. This weld technique has been successfully applied during the production of grid segment with >97% success rate.

3.1 Strength of CuOF welds

Strength of half hard copper is attributed to the strong lattice structure achieved during cold working at the time of base plate manufacturing. However, the heat imparted during welding removes or reduces the effect of this cold working, depending on the type of heat source. This results in loss of strength in fusion zone and heat affected zone. Table 2 shows the comparison of weld strength with respect to base material for some of the similar and dissimilar welded connection for TIG and EBW processes.

TABLE 2. STRENGTH OF WELDED CONENCTION FOR VARIOUS COMBINATION

Configur-ation	Material	Welding process	Thk. of weld (mm)	Base material strength (MPa)	Strength of weld (MPa)	Failure location
Butt weld-Stub to Plate)	CuOF to CuOF	EBW	13	240	238, 237	weld
			15	240	219 to 232	weld
			30	240	226, 228	weld
Butt weld-Tube to Tube welding	CuOF to Inconel	EBW	2	240	234 to261	CuOF base material
	SS to Inconel	EBW	5.5	485	622, 626	SS base material
	SS to Inconel	TIG	1	485	683, 674	SS base material
	SS to SS	TIG	1-2.6	485	556 to 694	SS base material

It may be noted that, CuOF is unalloyed grade of copper and it is not possible to regain the strength by any means other than cold working. Further, conventional codes (ASME / RCC-MR) do not addresses such practical limitation encountered during the welding of pure copper and dissimilar material. The route adopted for the acceptance of this weld is to compare the achieved weld strength (listed in Table 4) with the design parameters, instead of comparing with the base material properties (as required by the code definition).

[1] This design along with the configuration and its realization has been protected and patent is filed for the same.

3.2 Weld Repair

Reparability of the weld seam is defined by, how the integrity of a defective weld joint is regained without compromising its quality. During the mass production, it is very likely that some weld joints show discontinuities during non-destructive evaluation or functional tests and if it does not fulfil the acceptance criteria defined by codes, they are considered as ‘defective’ weld seam. These discontinuities depend on the weld characteristics like welding process, joint geometry, configuration etc. It may be noted that acceptance criteria for some defects like linear porosity, cluster porosity, slag inclusion, solid inclusion, root oxidation are stringent in IVH compared to ASME and EN. For the component like grid segment, which involves large number of welded connection, it may not be practical idea to reject the complete efforts due to defect on single weld connection. At the same time, it is equally important to ensure that this defective weld is repaired appropriately according to the acceptance limits of codes. For the conventional process like TIG, the repair possibilities and their methodology (i.e grind out and reweld, may be with filler) is established. However, for the process like electron beam welding, the management of a weld repair requires special attention due to the fact that: (1) this process demands precise weld edge preparation, which may or may not be available during the time of ‘re-welding’ (2) filler material addition is not possible and therefore the possible option to repair by electron beam is either to re-fuse the weld seam or to cut and re-weld it. During re-fusion, filler material addition is not possible and therefore the weld parameters shall be such that the material loss is minimal. On the other hand, in case of cut and re-weld, there may be a case where the removal of the complete heat affected zone is not possible due to design features of the components. In such a situation, the parameters of new weld shall be such that it does not degrade the mechanical properties of the heat affected zone by repeated heat cycles. (4) Electron beam size is very narrow, therefore the beam must strike exactly at the location of defect. Therefore, the coordinates of volumetric defects shall be carefully identified during the evaluation of non-destructive examination. Also, there may be a requirement of cross checking of the type and size of defect by multiple evaluation techniques or by using the combination of more than one technique.

The flow chart presented in the Fig. 7 shows the typical methodology adopted for the management of weld repair for the defective weld connection between base plate and water connector stub. Feasibility and repeatability of this method has been established by performing weld repair on the test coupon. The repaired weld has been qualified for its integrity through non-destructive examination and for its mechanical strength through destructive examination.

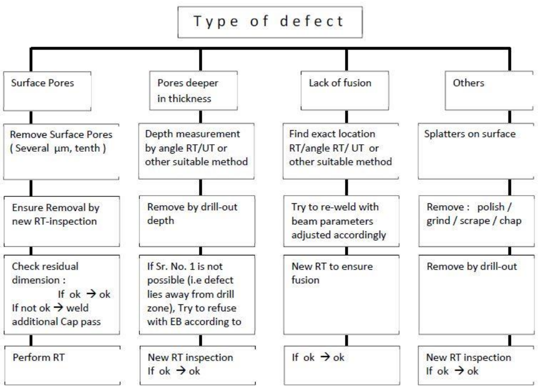

FIG. 7. Repair methodology for a typical electron beam welded connection for a grid segment

4. POST INSULATORS

Post Insulators (PI) used in the extractor and accelerator system provide the electrical isolation upto -90kV across the grid and to support them structurally. From the electrical point of view, electrostatic shields have been shaped and spaced according to the required isolation level and to limit the electrical stress upto 3.5kV/mm. On the other hand, mechanical loading comprises of multi directional differential stresses and deformations at the junctions of metal to high purity alumina.

Configuration of the post insulator comprise of high purity alumina cylinder (of dia. 50mm and length 100mm), metallic flanges and electrostatic shields. Conventionally, the connection between alumina cylinder and metallic flange is realized through brazing, which consist of Silver based brazing paste. However, due to ITER's radioactive environment, the use of silver in the system is restricted. An alternative technology, to meet the functional and system requirements, uses bolted connection between ceramic and metal, where threads are provided in ceramic holes. Helical inserts (Fig. 8) have been used as a soft compliant layer to avoid the damage of threads due to tightening pre-load. Electro-mechanical design of this configuration has been performed in two phase: (1) Finite Element Analysis (FEA) approach in achieving and verifying the basic configuration and (2) the validating the design by manufacturing 1:1 prototype and testing them for mechanical loading and electrical isolation test. Mechanical load test, has been performed by mounting the two post insulators in series and applying tensile load from the center to simulate the realistic loading. The breaking load observed during this testing was 13kN to 16kN, which is as estimated from the FEA simulation and it also, complies with the requirement of 10kN for the functionality. Validation for the electrical isolation has been carried out by applying the voltage upto 140kV for three hours in vacuum and leakage current observed was in the range of 100μA. After the satisfactory results of prototype testing, production of post insulators has been completed with complying to the specification requirements. The leakage current during electrical testing at 140kV was in the range of 280 to 500 μA for a batch of four insulators.

(b) (c)

(a)

FIG. 8. (a) Configuration of a post insulator (b) 'as manufactured' post insulator (c) fracture characteristics during the mechanical test

Apart from the electrical and mechanical test, an important consideration during the manufacturing design was the dimensional tolerances on the sub-component and assembly of post insulator. The length and parallelism tolerance have been defined in such a way that (1) bolt preload does not overstress the ceramic during assembly and (2) meets the overall alignment requirements of the accelerator. The dimensional inspection for the production set of 40 Nos. shows that the targeted values of tolerances have been achieved for length of 176mm +/- 0.06 and parallelism of 50 microns, in assembled conditions.

5. MATERIALS FOR ADAPTABILITY IN RADIATIVE ENVIRONMENT

Due to ITER's radiative environment, the contents of Co, Nb and Ta in SS base material is restricted to 0.02wt%, 0.01wt% and 0.01wt%, respectively, in stainless steel materials. However, for the thickness <10mm, it is difficult to get the material with these constraints, especially when required in small quantity like in present case. On the other side, for the material thickness >10mm, such material is normally available and sometimes with the values far below the required one. For example, the average Co wt% of 16 T of SS plates with thk >10mm, procured for the present component, is 0.024. Considering this situation, an approach of 'budgeting and balancing', of such chemical elements has been adopted such that, locally they may exceed the limit but the overall quantity of these elements into the system remains in compliance with the original projection. Additionally, material for some of the components has been replaced by Aluminum alloy (where these elements are found to be below detectable limits, as confirmed by chemical analysis) keeping the functionality unaffected. Another restriction due to radioprotection requirement is on the usage of Silver, due to its probable transmutation into the Cadmium under the neutron environment, which increase in the gas load of the system. However, for some components like capacitors, use of Silver is unavoidable for brazing of the ceramic to copper plate. For such cases, from the weight of silver, estimation of the production of Cd is made considering the energy spectrum at the location of component with respect the tokamak, and its possible impact on the vacuum pumping system is assessed.

6. HANDLING OF NON-CONFORMITIES AND DEVIATION

Quality interventions are necessary to ensure the adherence of manufacturing activities with the laid procedures. As the Ion source is one of its kind manufacturing, strict quality protocols (in some cases, over and above to

ITER quality procedures) have been incorporated in the Manufacturing and Inspection Plan (MIP). Registering each non-conformities (be it a small or large) in form of Non-conformity Report (NCR) is the evidence of the close compliance of established protocols and showcases an effective quality system. Additionally, it is equally important to recognize the modifications which emerge during the execution, by the involved agencies due to various reasons like manufacturing feasibility, design modification, interfaces, inspectability and technological limitations, which subsequently handled in form of Deviation Requests (DR). While NCR and DR are the inherent part of the manufacturing, it is equally important to justify them with the technical assessments (like FEA, experimentations, prototyping, imposing additional inspection / test etc.) and check that they do not impact the overall functionality of the system. Table 5 shows the contribution of various factors for NC and DR.

TABLE 5. CONTRIBUTING FACTORS FOR NC AND DR

Contributing factors for NC	%
Welding and qualification related	31
QA related	7
Materials related	28
human errors	14
process related	3
machine errors during machining	17

Contributing factors for DR	%
Material / chemical composition related	8
Manufacturing process related	24
Manufacturing design / feasibility related	24
Inspection and tests related	12
Vacuum / IVH related	8
Functional design related	24

7. SUMMARY

Technologies for realization of ITER size negative Ion source have been developed for most of the components, in compliance with the design and functional specification. Some of the key outcome from this realization are: (1) 'angled' grid segment manufacturing remains a challenge, even after establishing the complete manufacturing procedure through 1:1 prototype. Each segment has to be handled with careful monitoring at all the stages of production (2) Welding for vacuum boundary connection according to ITER requirements, is one of the most critical activity in terms of process selection, configuration and its qualification for timely execution of the project (3) Inspite of sufficiently detailed and thoroughly detailed specification, there are possibilities of deviations to suit the manufacturing needs, which have to be accommodated without impact on the function of components (4) Prototyping is essential for the components where no past experience is available to establish the feasibility and to unfold the uncertain areas of manufacturing (5) It is essential to be a 'Technical Partner' to 'Contractor' for every challenge they come across to fulfil the specification requirement, for the success of such a challenging project.

Significant learnings generated from this manufacturing is expected to provide the guideline on manufacturing design for upcoming ITER ion sources with similar challenges for seamless manufacturing with reduced time and efforts.

8. REFERENCES

[1] A.Chakraborty et al., Diagnostic Neutral Beam for ITER – concept to engineering, IEEE Trans. on Plasma Sci. (2010) 38, 248.
[2] M. Bandyopadhyay et al., Beamline optimization for 100keV diagnostic neutral beam (DNB) injector for ITER, IEEE Trans. on Plasma Sci. (2010),38, 242.
[3] M. J. Singh et al; Rev. Sci. Instrum. (2010)81, 013305.
[4] EN 13599, Copper plate, sheet and strip for electrical purposes, May 2002
[5] J. Joshi et all; Fusion Engineering and Design 123 (2017) 366–370
[6] ITER Vacuum Handbook, Attachment 1
[7] ASME Sec VIII Div. 1
[8] EN ISO 10675-1

ACKNOWLEDGEMENTS

Authors acknowledge the technical support from ITER Organization and IPP, Garching during the execution of this project.