DEVELOPMENT OF TECHNOLOGY FOR FABRICATION OF PROTOTYPE ION EXTRACTION GRID FOR FUSION RESEARCH

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Abstract

Steady state Superconducting Tokamak (SST-1) has a provision for positive hydrogen ion based Neutral Beam Injection (NBI) system for heating plasma ion temperature to \(\sim 1\) keV. This system has capability of injection of neutral hydrogen beam power of 0.5 MW at 30 kV. In second phase of SST-1 operation the same injector could provide NB power of 1.7 MW at 55 kV. Considering neutralization efficiency and beam power loss at different beam line components the required extracted hydrogen ion power from ion source would be 1 MW at 30 kV and 5 MW at 55 kV respectively. This implies that extracted hydrogen ion current is 35 A at 30 kV and 90 A at 55 kV respectively. Ion beam optics calculation shows that maximum hydrogen ion current can be extracted at 55 kV from 8 mm diameter single shaped aperture in 3 grid accel-decel extractor system is \(\sim 116\) mA for beam divergence of 1°. Therefore, to extract 90A ion current from plasma ion source the required numbers of shaped apertures are 774 which are accommodated in extraction area of 230 mm \(\times\) 480 mm. During beam operation extractor grid received heat load of \(\sim 175\) W/cm\(^2\) and the same is removed by dense network of 22 semicircular (\(r=1.12\pm0.05\) mm) cooling channels embedded between the rows of shaped apertures drilled in OFHC (Oxygen Free High Conductivity) copper grid base plate of thickness 4.2 mm. The required surface flatness of OFHC copper plate is 100 \(\mu\)m and positional tolerance of aperture is \(\pm 60\) \(\mu\)m. Fabrication of ion extractor grid is very complex and several technology requirements are involved e.g., Friction Welding, CNC machining and copper electro-deposition. This paper shall describe details of prototype development for manufacturing of extractor grid.

1. INTRODUCTION

Neutral Beam Injection (NBI) is a workhorse for tokamak plasma heating and current drive [1-6]. The technology of producing neutral beam power is very complex. Neutral beams of a given energy are produced in the following sequences: first plasma is formed in Plasma box. Then ions from this plasma box are separated, extracted and accelerated to a desired energy by an ion extractor system. The accelerated ions are neutralized by passing them through a gas cell called neutralizer. Neutralization occurs by charge exchange process. Un-neutralized ions are separated and deflected by bending magnet to a dump. The energetic neutrals, uninhibited by the tokamak magnetic field, are injected into plasma for the purpose of heating, current drive, plasma rotation and fueling. First phase of SST-1 operation needs neutral hydrogen beam power of 500 kW at 30 kV to raise ion temperature of \(\sim 1\) keV. In the second phase of operation the required neutral beam power is 1.7 MW at 55 kV [7]. The distance of SST-1 plasma center from ion source is about 7 m. During transportation of beam to tokamak plasma, beam power loss is takes place at different beam line components (e.g., neutralizer, magnet liner, ion dump, V-target and tokamak duct etc.) and to reduce such beam power loss the required beam divergence is 1°. The neutralization efficiency is also varied with beam energy. Keeping in mind all these factors to meet above mentioned NB power, the required extracted ion beam power from ion source would be about 1 MW at 30 kV and 5 MW at 55 kV respectively. This is a long dynamic range of high-power ion beam requirements. To obtain hydrogen ion beam power of 5MW at 55 kV, the extracted ion current is \(\sim 90\) A. Ion beam optics simulation code AXCEL-INP [8] is used for design 3 grid accel-decel ion extractor system to meet SST-1 requirements [9-14]. Simulation result shows that 116 mA of hydrogen ion current at 55 kV can be obtained from single aperture of 8 mm diameter. Therefore, to obtain 90A hydrogen ion beam current the required number of shaped apertures is 774 drilled on 4.2 mm thickness OFHC copper base plate with positional tolerance of \(\pm 60\) \(\mu\)m. Extraction area is 390 cm\(^2\). During beam operation extraction grid plate received heat load of 175 W/cm\(^2\) and to remove the same efficient cooling is provided with dense network of wavy semicircular (\(R=1.1\pm0.05\) mm) water cooling channels embedded between the rows of apertures. Keeping space for laid down of cooling channels between the rows of apertures the grid transparency of \(\sim 36\)% is considered. This required grid area is 1100 cm\(^2\). Considering some additional space for water manifold and holding provision the approximate size of extractor grid area is 40 cm \(\times\) 60 cm. The required surface flatness of grid plate is 100 \(\mu\)m. All these required critical dimensional tolerances leads to complexity in fabrication of extractor grid. The development of extractor had to undergo process qualification of various fabrication steps and construction of
various prototypes. This paper presents results obtained from the experience of getting prototype extractor grid fabricated. The work presented here provides an initiative for establishing a front-end complex technology of multi-megawatt neutral beams in our country. This is required for fusion reactors. The paper is organized in the following way: description of PINI (Positive Ion Neutral Injector) ion source is given in section 2, section 3 deals with critical feature of fabrication of grid, in section 4 methodology of grid fabrication is described, section 5 mentioned about development of technology involved in fabrication of grid, in section 6 acceptance test results are given and conclusions are given in section 7.

2. DESCRIPTION OF PINI ION SOURCE

SST-1 NBI ion source is similar to TEXTOR PINI ion source [15-17]. The cross sectional view of this type of ion source is depicted in fig.1 and 3D CAD view [18] is depicted in fig.2. Plasma is produced inside vacuum chamber called plasma box of racetrack type copper structure 58 cm in length, 31 cm in width and 19 cm in height. The plasma is generated by 24 heated filaments seated on back plate. Each filament is made up from 15 cm long and 1.6 mm diameter tungsten wire. The water channels are CNC milled grooves in the wall of plasma box and back plate. Permanent magnets (Samarium cobalt: SmCo$_5$) of surface field strength of 4 kG are placed in checkerboard pattern all around the walls of the plasma box and back plate to confine the plasma. This type of magnetic configuration would give uniform plasma density distribution over extraction grid surface area. Ion extractor system consists of 3 grid accel-decel system [9]. The first grid which is in contact with plasma is called acceleration grid and connected to high voltage (55 kV max.). The second grid is at negative potential (-2 kV) is called deceleration grid. The last grid, earth grid is maintained at ground potential. Acceleration, deceleration and earth grid are seated on coaxial race tract type acceleration grid holder box, deceleration grid holder box and earth grid holder box respectively (fig.2). All the three grids are subjected to different voltages. This is achieved by isolation of each grid holder box by post insulators (fig.2). The intermediate grid separation is also maintained by these post insulators. Neutralizer is started just after earth grid and supported by flange at ground potential. The extractor system and plasma box are fixed on HV flange which is connected to titanium ring. The entire system is assembled inside porcelain cylinder of 1 m long, outer diameter of 98 cm and inner diameter varies from 90 cm to 94 cm. This porcelain cylinder acts as vacuum envelope and also serves as electrical isolation in different components of ion source.

3. ION EXTRACTOR GRIDS AND ITS CRITICAL FEATURES IN FABRICATION

Main function of the extractor system is not only provide an acceleration space for accelerating of ions without any gas breakdown, but also to prevent electrons from streaming back to plasma box and to extract ions at
ground potential. For long pulse operation, provision of network of water cooling channels has to be made for removing the heat deposited on copper grids. Construction of grids has to be such that they are not stressed under the thermal loads. This allows optics of beams not to be degraded. The target is to extract 90A of hydrogen ion current at 55 kV in 774 beamlets with current density 230 mA/cm². In SST-1 NBI system the beamlets are focused to 7 m vertically and 5.4 m horizontally with net beam divergence < 1° [9]. Extractor grids are made up of OFHC copper. This is soft material for easy CNC (Computer Numeric Control) milling of wavy cooling channels and drilling number of shaped apertures in a thin base plate. OFHC copper material has also advantage of high voltage hold-off capability and higher hydrogen embrittlement. Design of extractor grids is most complex due ion optical requirements of various critical dimensional tolerances [19]. Achieving of these tolerances are real challenges in fabrication. Development of extractor grids had to undergo process qualification of various fabrication steps and construction of various prototypes. Acceleration grid is most complex in design and fabrication in comparison to others. In this paper we shall discuss critical aspects of design of acceleration grid and establishment of technology involved for manufacturing. Acceleration grid is splits into two halves and each half contains 387 numbers of shaped apertures and 22 numbers of cooling channels. Fig.3 depicts the OFHC copper base plate of size 450 mm (W) × 400 mm (L) on which 22 number of cooling channels, inlet and outlet manifolds are CNC milled. Manifolds are connected to common header which is friction welded stub pipe of 8 mm inner diameter. Out of 22 cooling channels one is straight rectangular cross-section (1.5 mm × 1 mm) and remaining 21 are wavy semicircular of radius R1.1±0.05 mm. After waxing and silver conductivisin of cooling channels and manifolds grooves 2.5 mm thick OFHC copper electro-deposited. Wax is removed from these grooves. Then final machining work is done for drilling 387 shaped apertures and milling of outer contour. Fig.4 shows 2D drawings of final machined acceleration grid half. Left half of this drawings depicts the inlaid cooling channels and inlet manifolds. Various dimensional tolerances are depicted. Extraction area has thickness of 4.2±0.05 mm where 387 shaped apertures each of diameter of 8+0.1/-0.0 are drilled with position tolerance of ±60 µm. A, B and C are representing reference holes required for assembly of three grids.

Shaped aperture (shown in enlarge view P in fig.4) has notch of thickness 0.2 mm and its upper and lower points have dimension 2.8±0.05 mm and 2.6±0.05 mm with respect to bottom of the plate. This is most critical dimension for CNC machining. The required surface flatness of OFHC copper plate is 100 µm. Fig.5 depicts the final CNC machined and electro-polished acceleration grid half. E, F, G and H are counter bore aperture used for fixing grid half on grid holder box shown in fig.2.
4. METHODOLOGY FOR EXTRACTION GRID FABRICATION

Fig. 6 depicts the various fabrication steps are followed during manufacturing of extractor grid. It begins with Friction Welding (FW) of 12 mm diameter SS304L stub rod on OFHC copper base with penetration length of 2 mm shown in fig. 6 (a). FW is chosen because it a circumferential weld joint between dissimilar metal and joining strength greater than OFHC copper and lower than SS304L metal. After FW on base plate, substantial mechanical machining work e.g. milling and drilling can be done without loss of weld joining strength. In this respect FW has an advantage over other welding. Then OFHC copper base plate is mechanically CNC machined for making cooling channel and manifold grooves and drilled hole through FW stub rod which becomes stub pipe of inner diameter 8 mm shown in fig. 6(b). Actual size acceleration grid half base plate with CNC milled cooling channel and manifold grooves which are connected to FW stub inlet and outlet pipes are shown in fig. 3.

These cooling channel and manifold grooves are filled with wax and surface of the wax is conductivising with silver paint shown in fig. 6(c). This would make electrical conductivity of entire upper surface of base plate which is required for electro-deposition of OFHC copper on this base plate. This wax filled base plate is now placed inside electro-deposition bath and 2.5 - 3 mm thick layer of electrodeposited OFHC copper layer formed on this base plate shown in fig.6 (d). Then the base plate is heated to 80°C and wax is removed from cooling channel and manifold grooves and then machining done for final thickness. In this way embedded cooling channel and manifold grooves are formed shown in fig. 6(e). It is to be noted that in the electrodeposition technique copper is deposited on the base plate in the ionic form and joining strength is equal to tensile strength of OFHC copper base plate. For this reason electrodeposition technique is very successful. Making of embedded cooling channels have also tried out by vacuum brazing of sandwich of two grid plates. It is observed that some cooling channel is blocked due to flow of brazing material during brazing process. During beam operation acceleration grid received heat load of ~ 175 W/cm² and to remove this heat load cooling water of velocity 13 m/s is passed through the cooling channel and pressure drop is 9 bar. Due to this high heat load and high water pressure, vacuum brazing joint over cooling channel is opened up and water leakage appears which causes accident in experiment. This type of accident generally does not occur in grid where cooling channels are made by electrodeposition technique. Finally apertures are drilled and CNC milling work is carried out for final thickness and outer contour of the grid shown in fig. 6(f). Thus manufacturing of grid involves three technologies e.g. (i) Joining of dissimilar metals of SS304L rod to OFHC copper base plate by Friction Welding (FW) for making stub pipe which acts as water header to supply water to the cooling channels inlaid in between the rows of the apertures (fig.4), (ii) CNC machining for milling and drilling work with specified tolerances and (iii) Electrodeposition of copper for making embedded water cooling channels. None of the Indian industry has expertise in these technologies as a result manufacturing of grid could not take place. In SST-1 NBI system, we have only one spare set of extractor grid from PVATePla AG, Germany [18] who manufactures the PINI ion source for SST-1 NBI. This spare set of grid may be used any time in future if any unfortunate water leakage occurs during beam operation from grids due to high voltage breakdown in the intermediate grid space. Vendor
may quote very high price for extra set of grid and longer delivery time. This may lead to long shutdown of the NBI experimental programme. Considering these eventualities, we have initiated the above mentioned technologies for manufacturing of extractor grid in India. The following section shall describe the prototype development activity for the same.

5. TECHNOLOGY DEVELOPMENT FOR FABRICATION PROTOTYPE ION EXTRACTOR GRID

5.1 Joining of dissimilar metals by Friction Welding for making water header

During beam operation acceleration grid received heat load of \( \sim 175 \text{ W/cm}^2 \) and to remove such heat load the required water flow velocity through cooling wavy semicircular cooling channel is about 13 m/s and expected pressure drop is about 9 bar. SS304L Stub pipe connected to grid plate is supply water to the cooling channels. The strength of joint of stub pipe and OFHC copper grid base plate must sustain such hydrostatic pressure. This has been achieved by joining dissimilar metals of SS304L rod of 12 mm diameter to OFHC copper base plate by Friction Welding (FW). Friction Welding parameters are established on prototype OFHC copper sample of 100 mm \( \times \) 100 mm \( \times \) 20 mm shown in fig.7. Mechanical properties of the Friction Welded joint is tested and result shows that joining strength is 264 MPa and hardness at FW area is 317 HV. Fig.8 depicts the actual size OFHC copper grid base plate (440 mm \( \times \) 330 mm \( \times \) 20 mm) with two friction welded stub rods. Mechanical drilling work on these two stub rods done and 8 mm inner hole is made in each rod. In this way two stub pipes each of 8 mm inner diameter and 12 mm outer diameter are formed which shall be used for inlet and outlet water header to supply water to grid manifolds and cooling channels. Extractor grids are placed inside vacuum of \( 10^{-4} \) Torr so leak tightness is the FW joint is tested with heating the plate to temperature of 210°C for 5 cycles. The leak rate is \( 1.5 \times 10^{-10} \text{T-l/s} \) which is satisfactory and acceptable.

5.2 CNC machining of OFHC copper Grid base plate

Fig.9 illustrates prototype grid plate of size 150 mm \( \times \) 60 mm \( \times \) 10 mm with 4 number of wavy semicircular (R1.1±0.05 mm) cooling channels which are connected inlet and outlet manifold. Each manifold is connected to respective water header. Dimension of cooling grooves are measured by ZEISS 3D CMM (Coordinate Measurement Machine) and result shows all cooling channels are with in specified tolerance. On this plate layer OFHC copper electrodeposition of 2.5 mm thick is done. Then final machining is done for drilling 19 numbers of apertures each of diameter 8 mm with position tolerance \( \pm 60 \text{ µm} \) and also milling work done for final thickness. Machining of drilling 387 apertures each diameter 8 mm is successfully carried out on actual size of 400 mm \( \times \) 350 mm \( \times \) 10 mm of OFHC copper grid plate shown in fig.10.
5.3 Copper Electro-deposition for making embedded water cooling channels in Grid base plate

Electro-deposition of copper on prototype grid was carried out from a solution containing copper sulphate (180-200 g/litre), sulphuric acid (38 to 40 ml/litre) and chloride (30 to 40 ppm) at a current density of 2 A/dm$^2$ for 100 hours. The technique of periodic reversal (PR) process was used during electrodeposition in which the polarity was reversed with time, where a 20 sec electro-deposition was followed by a 4 sec reversal.

Before doing copper deposition on prototype grid, studies were carried out on test specimens from electrolyte mentioned above with different operating conditions for characterizing the properties of the deposit. Metallurgical studies indicated nucleation of fine grains (fig. 11) from substrate/deposit interface grew into long and coarse columnar grains. The extent of grain growth was relatively larger in the deposit made with higher current density. In 1 mm thick specimen made with 2 A/dm$^2$ current density, appreciable grain growth initiated only after a deposit thickness of about 0.25-0.3 mm as shown in fig. 12. In the case of 3-mm thick specimen made with lower current density of 1 A/dm$^2$ no significant grain growth was noticed till a deposit thickness of about 2.5 mm was reached. For measuring the tensile strength, test specimens was prepared by depositing thick copper on passivated stainless steel base substrate machined to the desired shape and its separation. The specimen exhibited yield and tensile strengths of 152 MPa and 252 MPa respectively. The percentage elongation of the specimen was 20 (gauge length 550 mm). In comparison to OFHC (Grade 10100), the electroformed copper specimen exhibited much higher yield strength and lower ductility. Detailed studies carried out and results obtained for characterization of the deposit properties was described elsewhere [20].

Test coupons made of copper were also subjected to electrodeposition along with prototype grid plate for measurement of micro hardness, electric conductivity and micro structure. Optical micrograph of electrodeposited copper with and without OFHC copper base substrate is shown in Fig.11 and 12 respectively.

In electrodeposited layers, fine grains with directional characteristics are seen near the interface. Towards the outer surface, coarser grains with less directionality are observed. The electrical conductivity was 101± 1 % IACS with micro hardness values 56 to 61 HV5.

Fig.13 depicts prototype grid sample with milled cooling channels and manifolds grooves filled with wax and conductivising with silver paint. Then electrodeposition of 2.5 mm thick copper done on the entire surface of the grid. After electrodeposition, wax was melted out by heating the grid piece to 80°C and flushing with suitable solvent. Then final machining done for drilling 19 numbers of apertures each of diameter 8 mm and milling for final thickness shown in fig.14.
7. ACCEPTANCE TEST RESULTS

Quality of friction weld joint of SS304L rod to OFHC copper plate is tested first with mechanical properties e.g. joining strength and hardness at weld area by making suitable samples. The result shows that joining strength is 264 MPa and hardness at weld area is 317 HV. Each FW stub pipe of 8 mm ID (after drilling hole on stub rod) is pressurized with 20 bar pressure for 1 hr. Then leak tightness of FW join is tested under heating condition. One stub pipe is connected to helium leak detector and thermocouple if placed inside other stub pipe (fig. 15). A heating coil is wrapped around the actual size OFHC based plate and heated to 210°C for 5 cycles with 30 min heating 1 hr cooling. Leak rate is $1.5 \times 10^{-10}$ T-l/s which is acceptable. Various dimension of CNC machined test grid piece is measured by ZEISS CMM and result shows that all dimensions are within specification except surface flatness of 200 µm which is beyond specification value of 100 µm. During electrodeposition on OFHC copper on machined prototype grid if any blockage occurs in cooling channel is checked by Liquid Crystal Display (LCD) display. In this technique LCD is spread over prototype grid surface and 40°C hot water is passed through inlet stub pipe header and water flows through 4 numbers of wavy semi-circular cooling channels (fig.16) and exit through outlet header. The colour change of LCD would confirm the continuity of the channels. Mechanical and electrical properties of electrodeposited OFHC copper are tested with samples made during electrodeposition. The result shows that tensile strength is 252 MPa, micro hardness is 61 HV, electrical conductivity is $101 \pm 1$ % IACS.

8. CONCLUSIONS

Technologies involved in fabrication of extractor grid are very complex and requires integration of several disciplines of engineering with physics. The development of an already existing technology elsewhere is like rediscovering a wheel, a process to which there is no alternative. This is because the data on every step of route to realizing a system is not available, partly because it is not documented and partly because it forms an intellectual property. Further, to get the maximum performance requires fabricating and operating a system at its limiting values of several variables of control parameters. Tuning a system to yield the best performance, quite often, consists of growth of performance curve based upon variation of several parameters of the system. This tuning process is sometimes specific to a system. Generally, the data on tuning procedure is not put in public domain. This is the case with the extractor system for NBI as well. It is clear that a real database can be generated only by prototype development under the real operating conditions. Due to these reason only few manufacturer are available worldwide. They demand very high price for supply of the grids. Sometime grids are
damaged by high voltage breakdown during operation and manufacturer refuse to supply the spare grid set which causes great delay in experimental schedule. None of Indian industry is available for manufacturing of extractor grid. Due to these constraints we have initiated prototype development of ion extractor grid to establish technologies involved in extractor grid fabrication in India. Results of various prototype development described above are satisfactory. This includes successful in-house development of various technologies for fabrication of extractor grid in India. Friction Welding for joining of SS304L rod to actual size OFHC copper grid base plate is successfully developed. Technology for making embedded cooling channels inside OFHC copper plate by electrodeposition of copper is established on prototype grid plate which is 1/10th of actual size. Mechanical machining work is carried on 1/10th of actual size of grid plate and various dimensional tolerances are achieved except surface flatness. The required surface flatness is 100 µm and achieved value is 200 µm. This can be controlled during machining of actual work with proper fixture at CNC machine platform. The experience obtained during this phase of prototype development shall be useful for fabrication of actual size ion extractor grid in India.

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