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Manufacturing prototypes for LIPAC beam dump

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Abstract

The purpose of the research is to define the most adequate manufacturing process for the dump of a linear deuteron accelerator. The deuteron beam can be pulsed as well as continuous with energies up to9 MeV. The maximum beam power is 1.12 MW corresponding to a beam current of 125 mA.

The requirements on the surface on which the deuterons will be stopped are quite demanding and the length and slenderness of the cone poses a considerable difficulty in the manufacturing process.

The design of the beam dump is based on a copper cone 2500 mm long, 300 mm aperture and 5 to 6.5 mm thickness.

Basically only two technologies were found feasible for the manufacturing of the cone: Electroforming and Electron Beam Welding (EBW).The article shows the main results found when manufacturing different prototypes.

Keywords:

Beam dump, Manufacturing, Electroforming, Electron beam welding

1. Introduction

The linear particle accelerator [1] (LIPAc) is a prototype of one of the two accelerators foreseen for the International Fusion Materials Irradiation Facility project (IFMIF). The LIPAc will not have a target and hence a dump is needed to stop the beam of deuterons. This beam dump will be cooled with water in order to remove the heat power deposited on its inner surface.

The design of the beam dump [2] has been driven by thermomechanical loads distribution studies and the radioprotection studies [3,4].

The beam dump cartridge is an assembly containing the following parts, see Fig. 1:

(1) The inner cone. The deuterons will impinge on its inner surface and the flow of water outside will remove 1.12 MW of generated heat. It is made of pure copper and it is 2.5 m long with an aperture of 300 mm.

(2) Outer cone or shroud. Together with the inner cone, it defines the channel for the cooling water flow. It is also made of copper.

(3) Cylinder. It supports the inner cone in the proper position and will hold the sensors (hydrophones and ionization chambers).It is made of stainless steel 304 L.

(4) Tip support. It provides the concentric positioning of the inner cone tip and the outer cone. It is made of pure copper.

(5) Rear flange. It closes the volume of the cylinder which is full of water. It also provides clamping support for the whole inner cone. It is made of stainless steel 304 L.

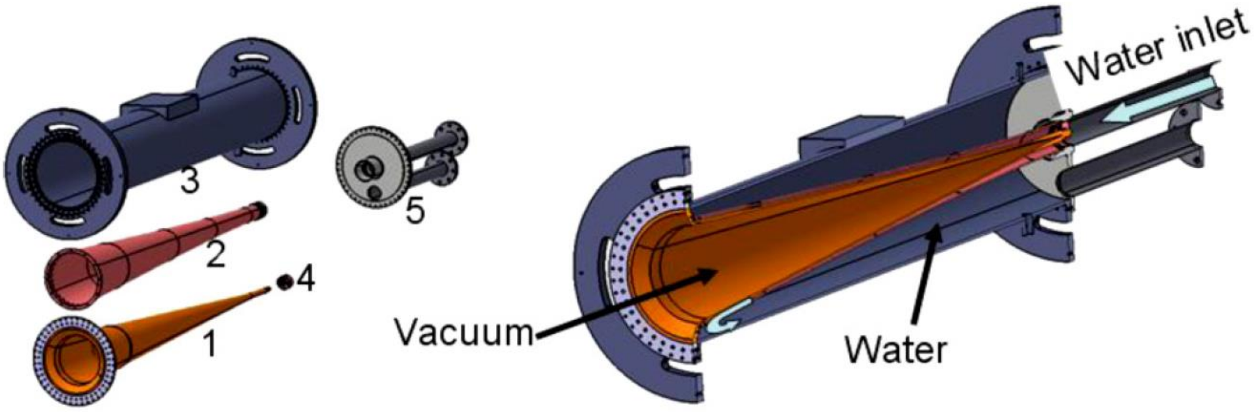

Fig. 1 Parts of the beam dump cartridge.

The inner cone is by far the most difficult part to produce and also the most critical. It is a very long and slender part with small thickness (5–6.5 mm).

The inner surface should be free from irregularities larger than 0.5 mm, in order to avoid hot points and peaks of thermal stresses. Due to the length of the cone this inner surface cannot be machined with conventional tools.

The bulk of the cone must be homogenous concerning the thermal and mechanical properties as a high heat flux must be transmitted to the cooling water through it. The heat flux can reach about 2 MW/cm^2 in some areas.

The zone of the vertex should be an empty volume with a tip really sharp because the beam reaches the zone with high energy density. It is very difficult to obtain such geometry by removing material at the bottom of a 2500 mm long cone.

The material chosen, pure copper provides good heat conductivity and acceptable levels of activation with neutrons flux but, the conventional technologies for welding are not applicable.

Given the demanding requirements on the final piece and the added difficulty of the geometry, some prototypes were done with the most adequate technologies: electroforming and EBW.

2. Manufacturing by electroforming.

The procedure consists in assembling a flange and a tip on a conical mandrel and then electroform the wall of the cone. The joints of the flange and the tip with the rest of the cone are obtained by the same electroforming and the mechanical characteristics are quite similar to those of a piece without joint [5]. Once the whole cone is electroformed, the outer surface is machined and subsequently the mandrel is removed.

Electroforming was chosen as a first option for manufacturing because of different advantages: it provides very pure copper, the grain size can be very small and hence obtain better mechanical properties, only two joints are required along the piece, the joints and the manufacturing process is at room temperature, meaning no residual stresses, and the geometry of the internal surface can be really accurate as it follows exactly the outer surface of the mandrel.

Electroforming has been used in the manufacturing of different parts in the Fusion field such as neutral beam injector grids or waveguide antennas.

For the manufacturing of the beam dump some challenges appeared:

- Concerning the flange, the joint stainless steel copper and the thickness to be obtained in the flange (up to 30 mm).

- Concerning the tip, the sharpness of the empty volume at the vertex.

- Concerning the rest of the cone, the irregularities on the joints and the coaxiality of the tip with the rest of the cone.

Some prototypes were manufactured in order to address theseissues.

2.1. Manufacturing of the flange by electroforming

The manufacturing of the flange is done by electroforming copper inside of a stainless steel ring with a similar shape than the one designed but leaving some excess of material, see Fig. 2. The outside diameter of the flange is 524 mm.

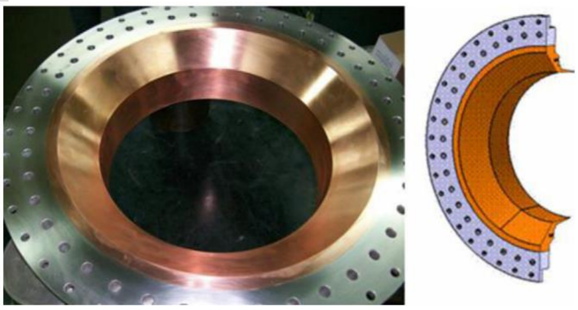

Fig. 2 Flange manufactured by electroforming Cu.

The outer stainless steel ring is needed to provide vacuum leak-tightness by using a metallic elastic o-ring. Simultaneously a good heat conductor is needed to receive the potential halo of the beam and, therefore a significant chamfer is made on the copper surface that connects the cone with the stainless steel ring.

The bonding of the copper with the stainless steel requires an interlayer of nickel several nanometers thick. The mechanical properties of such bonding were checked by performing tensile tests with cylindrical hollow specimens with and without joint.

Results of these tests are represented in Tables 1 and 2 for room temperature and 150◦C respectively. This last temperature is a value well over the maximum temperature foreseen for that area of the beam dump. The values of the Yield Strength (YS) are excellent. The cone is designed such that it will always work in the elastic field; nevertheless the values of the Ultimate Tensile Strength (UTS) are provided in the tables.

Table 1 Values at room temperature

T_{room}	YS [MPa]	UTS [MPa]	Strain at peak (%)
Cu ENJ[a]	309	421	6.8
SS-Cu	281	317	6.8

[a] Cu ENJ = samples made of electrodeposited copper with no joint.

Table 2 Values at 150 ºC

150 ºC	YS [MPa]	UTS [MPa]	Strain at peak (%)
Cu ENJ[a]	202	242	9.9
SS-Cu	236	268	4.5

[a] Cu ENJ = samples made of electrodeposited copper with no joint.

2.2. Manufacturing of the Tip by electroforming

The hollow conical shape of the tip should be very sharp because the distribution of the beam has a high power density in the axis and hence a large radius at the tip would derive in high thermal stresses.

It was not possible to machine a 2.5 m long aluminium mandrel with a sharp tip. This was due to the bending forces and vibrations that appeared when removing material near the tip. Therefore the tip of the inner cone was manufactured in advance by electroforming.

Different materials were used to manufacture the mandrels on which to electroform the Cu samples: aluminium, stainless steel, carbon steel. Once demoulded the Cu electroformed samples were cut in two and measured with an optical projector, see Fig. 3.

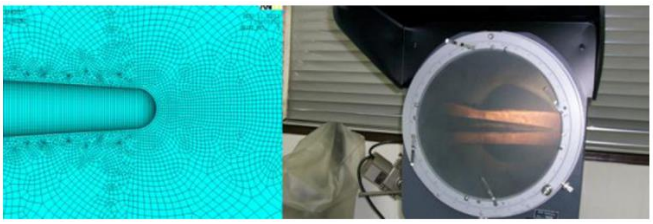

Fig. 3 Hollow tip of the inner cone.

The sharpest tip was obtained with the stainless steel mandrel, it has a radius of 0.6 mm. In order to have a security margin, the thermomechanical calculations were performed with FEM assuming a radius of 1 mm.

2.3. Electroforming the body of the cone.

The manufacturing of the body of the cone is done by electroforming copper on an aluminium mandrel.

A copper flange and a copper tip were assembled on a trunk-conical aluminium mandrel with the same conical angle than the definitive piece but 1500 mm in length, see Fig. 4.

The electroforming produced the joints of the flange and the tip at the same time that the thickness of the copper wall grew. It took about 21 days of continuous electroforming until a thickness of 6 mm or larger was reached all along the cone.

The cone was rotated 90◦ once a day and the baskets with the copper anodes were repositioned in the electrolyte bath in order to have a uniform growth of the copper wall.

The connection of the tip with the rest of the cone was a matter of concern because, irregularities in this connection could lead to higher number of ions stopped and hence to localized hot points.

Dedicated tests were carried out, making partial electroforming samples, using different materials for the mandrel (aluminium, PVC, PMMA), in order to asses the variations in the size of the irregularities.

With the aluminium mandrel some lumps and voids were found with values of 0.2 mm in height and 0.13 mm in depth respectively. These irregularities could derive from bubbles appearing due to the contact of aluminium with the electrolyte.

With the PVC mandrel, the irregularity obtained in the connection was smaller than 0.02 mm.

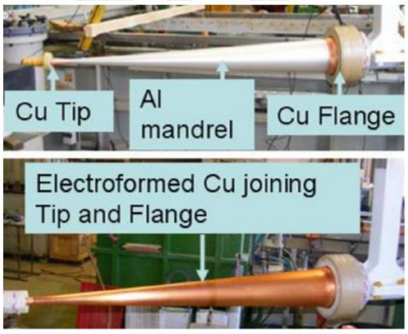

Fig. 4 Electroformed body of the cone.

With the PMMA mandrel, large irregularities up to 0.4 mm in size were found, probably derived from a lack of coincidence in conical angle of the tip and the mandrel or a misalignment during the assembly.

As a result, the best solution devised to obtain a negligible irregularity at the connection, would be to use a PVC ring at the zone of the aluminium mandrel where the connection with the tipis located.

2.4. Machining and demoulding of the inner cone.

The outer surface of the 1500 mm long prototype was machined in an Integrex Mazak machining centre. The machining was done with the aluminium mandrel still inserted in order to provide robustness.

It was necessary to develop and install a centring device in order to correct the concentricity of the Cu cone with the axis of the machine. The checking of the concentricity was done by measuring the thickness of the copper wall with an ultrasound gage in azimuthal direction and in two axial positions.

The deviation in concentricity achieved was 0.15 mm of the conical surface with respect to the flange. After finishing the machining there was a global variation in thickness of the wall of 0.2 mm along the whole cone. The roughness of the outer surface obtained was Ra = 2.59 µm.

Once the machining was finished, the inner mandrel should be extracted. This extraction was not an easy task because the copper is so tightly close to the aluminium copying even the roughness of the surface.

The extraction was achieved by using bolts pushing the copper cone away from the aluminium mandrel and simultaneously cooling down the mandrel with liquid nitrogen, taking advantage of the differential thermal expansion coefficient for each material: 23.6×10^{-6} m/(m◦C) for Al 6082 alloy and 17.0×10^{-6} m/(m◦C) for pure copper.

Some of the paint layer applied to protect the aluminium from the electrolyte during the electroforming remained stuck to the copper surface, so it was later on removed using ethyl acetate.

Finally the inner surface of the cone was cleaned with a solution of Citranox at 10% with deionized water at 55◦C and rinsed with alcohol.

3. Manufacturing by EBW

It was decided to build a prototype 1:1 of the cartridge in order to check the fluid-mechanical coupling in the cooling channel and the appearance of induced vibrations and also to discover problems in the design that could have gone unnoticed. The manufacturing of the inner and outer cone with EBW technique was decided in order to obtain an assembly with similar mechanical properties but in a cheaper and faster way than using electroforming.

3.1. Production of inner cone parts.

Fig. 5 shows the parts that were independently produced and later on joined by circular EBW. Parts with diameters smaller than130 mm were obtained from copper C-101 bars, by machining them in a lathe.

The inner surface of the tip of the cone was produced by Electro Discharge Machining using a graphite electrode.

Parts with larger diameters were obtained from Cu-HCP EN13599 copper sheet, starting with a 10 mm thickness sheet, truncated cones were shaped and longitudinal joints performed by EBW. Later on, each of these truncated cones was machined to final dimensions with male/female connections to the correlative parts.

Fig. 5 Parts of the EBW inner cone.

Some tests were done with MIG and TIG welding techniques for the longitudinal joints but they were unsuccessful assumedly because the high heat transmission coefficient of the material that spread the heat applied by the torche.

3.2. EBW of truncated cones.

Some ancillaries were designed in order to support the parts of the inner cone in place, that allowed the EBW in sectors, see Fig. 6. Once the truncated cones had some parts joined, the longitudinal bars were removed and a continuous pass of the electron beam was performed.

The correct values of the parameters for the electron beam were first investigated using specimens with the same copper material and with cylindrical geometry. Two sizes of the shoulder to stop the electron beam were used, one millimetre, to be used in the inner cone, and two millimetres, to be used in the outer cone of the beam dump.

Samples of these specimens were polished and attacked in order to check the continuity of the material in the joint. The results were that for the line where the electron beam passed, the grain size is abit bigger but there is perfectly continuous, on the other hand the zone of the shoulder is not continuous and it cannot be taken into account for forces and heat conduction.

The technique of EBW could be used for the manufacturing of the inner cone but, taking successive steps for the production, applying machining of the inner surface after joining two parts, in order to remove surface irregularities on the area where the power deposition takes place.

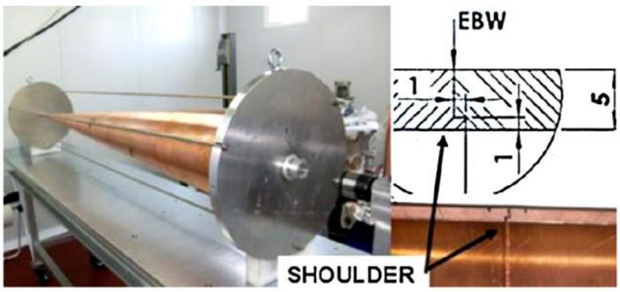

Fig. 6 Inner cone EBW ancillaries and geometry.

3.3. Acceptance tests.

The 1:1 prototype obtained by EBW was used to analyze the assembly process and some changes were proposed in the design that will be implemented in the final beam dump. We also got a more realistic feeling about the dimensional and geometrical tolerances to be applied for the manufacturing of the final beam dump. The reference manufacturing requirements are shown in Table 3.

Table 3 Reference manufacturing requirements

Geometrical tolerances	
Concentricity of circles along the cone	0.2 mm
Axis straigthness of the inner cone	0.2 mm
Roundness of the circles along the cone	0.1 mm
Flatness of the flange	0.25 mm
Azimutal uniformity of the cooling channel	5% gap

The outer surfaces of the inner cone and outer cone were analyzed by using a 3D measuring machine. For the inner cone these are the geometrical deviations measured: deviation in concentricity of 13 circles measured along the cone 1.769 mm, deviation in straightness of the axis is 0.960 mm, the deviation in roundness is 0.106 mm, and the deviation in flatness of the flange is 0.075 mm. Values for the outer cone are in the same order of magnitude.

These deviation values should be included in thermomechanical simulations to increase the precision of the results, as they affect the power deposition produced by the beam and hence the thermal stresses.

The gap between both cones that is actually the cooling channel through which the water flows, was also measured as it is of paramount importance for the heat transmission coefficient between inner cone and water. Uneven distribution of the gap would lead to an azimuthally variable temperature and hence a bending of the cone. 24 holes were drilled on the outer cone for the purpose of measuring differences in gap, after rotating the outer cone to the most convenient position a difference in gap of 1.7 mm was measured (8.5% of the gap), after measurement completion, the holes were threaded and closed with copper bolts tailor made for this purpose.

The inner cone is a vacuum vessel and therefore it should be tested to He leak. The 1:1 prototype was tested in order to check if it had any pores left due to a defective welding. The He leak measured was 1.27×10^{-11}Pa m^3/s for a base pressure of 2.6×10^{-4}Pa.

The outer surface of the inner cone together with the cylinder and the rear flange contain the water used for cooling at pressure 2.5 bar. Hydraulic leaktightness was checked at 4.5 bar using polymeric sealing rings in the 1:1 prototype, no leaks or dramatic drop of pressure was found.

In the final beam dump, polymeric sealing rings are to be avoided, instead elastic metallic rings will be used (helicoflex) in order to withstand radiation damage, but the same geometry and principles will be used.

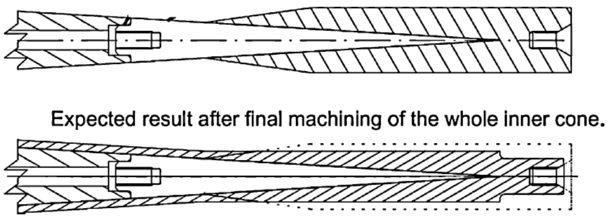

Fig. 7 Assembly of the tip on the mandrel.

4. Conclusions

The tests carried out provide a solid background for the definition of the manufacturing process for the final beam dump. Some material data has been obtained with tailor made tests like the mechanical characteristics of the stainless steel-copper joint produced by electroforming.

The effects of small defects like the non-perfect tip of the inner cone and the lumps and voids appearing during real manufacturing process were assessed via FEM analysis with realistic values.

Deviations in dimensions and geometry were measured for prototypes and they have been taken into account for the thermomechanical study. A good idea of the achievable tolerances was obtained.

Electroforming of copper proved to be adequate for the manufacturing of the inner copper cone. The electron beam welding technology could also be used alternatively with some intermediate steps of the inner surface machining added.

The 1:1 prototype manufacturing, assembling and checking procedures, unveiled some design problems and produced experience to be used in the specifications for the final beam dump.

Future plans for manufacturing the final dump include, modifications in the way the tip is assembled to the mandrel for electroforming, to ensure good alignment and minimize irregularities in the connection, (see Fig. 7). The fabrication of both, inner cone and cone and outer cone or shroud will be performed with the electroforming technique that produces smaller dimensional and geometrical deviations compared to EBW manufacturing technique.

Acknowledgment

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