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Electron Beam Welding of Triple Choke 11.4 GHz multi-cell linear structures

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Abstract

In the framework of the collaboration with SLAC and KEK laboratories one standing wave (SW) triple choke 11.424 GHz cell accelerating structure has been fabricated for the high-gradient RF breakdown studies as part of the breakdown research program.
An extensive experimental and theoretical program to determine a safe operating gradient for the future Next Linear Collider (NLC) is under way in SLAC.
Here we describe a triple choke hard copper cavity design using the Electron Beam Welding (EBW) method in order to investigate the high-gradient RF breakdown.

Introduction

Accelerating gradient is one of the crucial parameters affecting design, construction and cost of next-generation linear accelerators. RF breakdown is one of the major factors determining performance of high power RF components and RF sources. RF breakdown limits working power and produces irreversible surface damage. The high gradient RF breakdown phenomena is still an open problem and dedicated research and development on this field have been launched within the linear-collider community. The activity of testing high-gradient RF sections at 11.424 GHz for the next generation electron-positron linear collider is in progress in order to understand the breakdown mechanisms which limit the high gradient performance. An activity of design, construction and experimental tests of short 11.424 GHz high power standing wave (SW) sections started at INFN-LNF in the framework of a collaboration with SLAC and KEK laboratories [2].

The goal of the collaboration is to assess the maximum sustainable gradients in normal-conducting RF powered particle beam accelerators with extremely low probability of RF breakdown. These studies include experiments with different materials and construction methods for single cell standing wave accelerating structures. The most commonly used method of joining cells of such structures is the high temperature bonding and/or brazing in

hydrogen and/or vacuum furnace. These high temperature processes may not be suitable for some of the new materials that are under consideration.
An intense technological activity is therefore dedicated to build and test X-band accelerating structures operating at 11.424 GHz, using different materials and methods [3,4,5,6,7,8]. The main processes under investigation are the following: a) soft bonding (250-300) °C; b) electroplating; c) molybdenum (Mo) sputtering on copper, d) various alloys such as CuZr or CuAg, of which INFN will is focusing on the first three.

We authors of this article also propose to build the SW triple choke structures made of copper and molybdenum bulk, taking the cell-to-cell junction out of the electromagnetic field region[9] and by using the Electron Beam Welding method.

The motivation for the study of hard copper alloys came from results of the pulse heating experiments [10]and [11]. Basically, from these experiment the discs made of hard copper and hard copper alloys (CuCr, CuZr) had significantly less damage at 110 °C while the discs made of high-temperature annealed soft copper showed signs of surface damage at about 50 °C [10] and [11 and therein]. High power RF tests of a single-cell standing-wave structures made of soft copper, showed an excellent correlation with peak surface magnetic field and peak pulse heating temperature [12]. Since the high power RF tests of the hard-copper structures showed some improvement over soft copper the authors of this article are going to construct the triple choke hard copper accelerating structures.

The status and issues on the soft bonding, electroplating and molybdenum sputtering on copper will be discussed in dedicated forthcoming papers. This paper focuses the technological techniques for fabricating the SW triple choke structures made of hard copper using the Electron Beam Welding process as part of the breakdown research program.

Triple choke cavity electromagnetic design

Accelerating gradients on the order of 100-110 MV/m have been reached in dedicated and short standing wave X-band accelerating structures prototypes [11]. Since the major obstacle for the additional improvements to higher gradients is the RF breakdown we made a hard copper triple choke cavity in order to improve further on the performance in terms of accelerating gradient and safe operation. For this reason, the triple choke structure was designed [9] in order to significantly reduce the electric and magnetic fields on the RF joint. A copper version of this structure has been constructed by SLAC for high gradient RF tests.

Basically, the device under study is a single-cell in a 3-triple choke cell structure fed by a circular waveguide. The central cell is the cell of interest and operates at high gradient, while the adjacent cells are used to match the RF power from the input circular waveguide and to balance the electric field in order to have the maximum intensity in the central one. This scheme is that used at SLAC to represent the performance of a long accelerating structure composed of cells like the central cell in the test structure [13].

The solid model of the triple choke hard copper section designed at SLAC is shown in Figure 1, while its relevant dimensions are reported in Figure 2 [9]. The special gasket to separate vacuum and RF joint to test hard alloy structures is illustrated in Figure 1a. The electric equipotential lines plot and the on axis π-mode accelerating electric field profile [14] are depicted in Figure 3 and Figure 4, respectively. The picture shows a good match at the nominal operating frequency of ~11.424 GHz and the maximum field intensity in the central cell doubles that of the adjacent cells. Additional details for electromagnetic are described in reference [9].

Triple choke Copper section construction description

Some section samples have been made by the private company COMEB S.r.l. of oxygen free Cu (OFHC) using a numerical controlled lathe; each cell has been checked with a quality control test of the geometrical dimensions and the obtained machining precision is by ± 2.5 μm while the smoothness is about 30 nm. The surface finishing was obtained directly by mechanical machining with custom cutting tools (diamond mono-crystal), avoiding any particular polishing technique. The machining was done at constant temperature (by means of a proper fluid) in order to maximize the uniformity of the mechanical dimension of the cells as much as possible.

To improve the high power performance (e.g. discharge rate) structure fabrication procedures need to avoid the device heating at high temperature as is done in conventional vacuum brazing technique or use material with higher fusion temperature. As an example, electroplated structures (or hard copper) tested at higher power gave a breakdown rate similar enough to the breakdown rate of the brazed structures of same geometry but slightly higher than the clamped structures [2].

For the standard brazing procedure a high temperature is required in order to obtain a joint with good mechanical and vacuum tight properties. Generally a temperature of at least 700 – 800 °C for Copper is needed. This temperature is supposed to modify the morphological properties the material affecting its quality in terms of RF performance. For this reason additional low temperature procedures (or hard bonding) have been considered. Among these ones the Electron Beam Welding (E.B.W.) has been adopted for the device under study.

The main positive feature of EBW is the low thermal energy transferred to the piece; the second one is the total absence of other metals generally present in the joint among cells, when the brazing process is used.

By the inspection of Figure 5a, we investigated how much the distance h between the welding bath and the cavity inner surface can be controlled and reduced. Since it is not easy to obtain a distance h much less than (or of the order of) the copper skin depth at 11.424 GHz with the EBW method, a compromise between them is required. The EBW expertise confirmed that, too. This problem can be coped with the following two procedures.

1) Reduce h, increasing the precision of the welding in collaboration with the Company that has the Welding Machine. The distance h can also depend on the stability of the Welding Machine parameters (voltage, current, electron beam focusing);
2) Provide a good vacuum tight contact among cells in proximity of the inner surface.

Presently a proper shape of the contacting surface is shown in Figure 5b. The smaller plane on one side of the contacting surfaces will guarantee a good R.F. and Vacuum tight connection among cells. In this way if the width d is larger than h the accuracy of the position of the welding bath gives no problem.

In addition, the preliminary prototypes have been fabricated making a pre-bonding approach at 300°C for 1 hour before carrying out the final E.B.W. process, in order to prevent:

1) micro-gaps left by welding (on the cell surface);
2) accidental pocket air inclusions;
3) EBW damages in the internal surface of the structure (or welding contamination).

As a result, the pre-bonding vacuum leakage tests show a leakage of about 10^{-10} mbar litre/sec. Figure 6 shows a prototype solid model; Figures 7 illustrates the prototype after the EBW process; Figure 8 reports the welding region zoom of the prototype cross section after the EBW process. We observe no cracks in the fusion zone and in the heat affected zone. There are only small porosities at the root-side of the weld joint which are, however, within the limits of the specifications. The joints in the pre-bonding region demonstrated to work well and additional tests are in progress, too.

The following procedure has been therefore adopted for the final triple choke 3 cell structure:

a) Assemble of all the cells applying an axial torque of roughly 150 Nm as it is shown in Figure 9;

b) Precision machine of all the components by ± 2.5 μm. As an example, in Figure 10 is illustrated one cell.

c) Treat all the structure at 300°C for 1 hour in a clean vacuum oven for pre-bonding;

d) Check the vacuum tightness of all the joints with the Helium Leak Detector at a sensitivity less than 1.10^{-9} mbar litre/sec.

e) Prepare the structure for the E.B.W. process. All the assembling activity is conducted in a clean room at ISO 5 class (or 1000 class). Two companies have been involved in the E.B.W. process. Both of them have the task to cut and polish the prototypes in order to check the results.

The joint between the structure and the vacuum system can be seen in Figure1, while the gasket developed both for vacuum tightness and RF continuity is shown in Figure 1a. Vacuum tests of some gaskets made of silver, copper and gold as a function of temperature gave excellent results up to 250 °C for 24 hour.

Results and conclusions

The authors of this article carried out some tests with E.B.W. method on some prototypes. The melted zone is clearly visible showing no defects at the boundary or cracks between bulk and melted Copper. The distance h (check the pictures) cannot be reduced to less than under of 1 mm. The tentative to give more power to the beam could open to the melted bath the way towards the inside. In our case we get about 0.25 mm. Check of dimensional mechanical tests before and after welding gave minor difference. The chosen profile geometry of the welding region should guarantee a good RF contact among cells. The E.B.W. process seems to give a simple and efficient connection among the cells. For these reasons a 3-cell structure, with choke profile, has been machined and close to being completed. The program is to have the structure welded in a few weeks.

The possibility to study a reduction of the distance h has not been abandoned and is still under investigation. The distance h could be related to the precision at which the E.B.W. machine parameters (voltage, current, electron beam dimensions) can be fixed. For this reason another company, having a more up to date E.B.W. machine, has been chosen. First tests on dedicated prototypes seem to confirm the above method.

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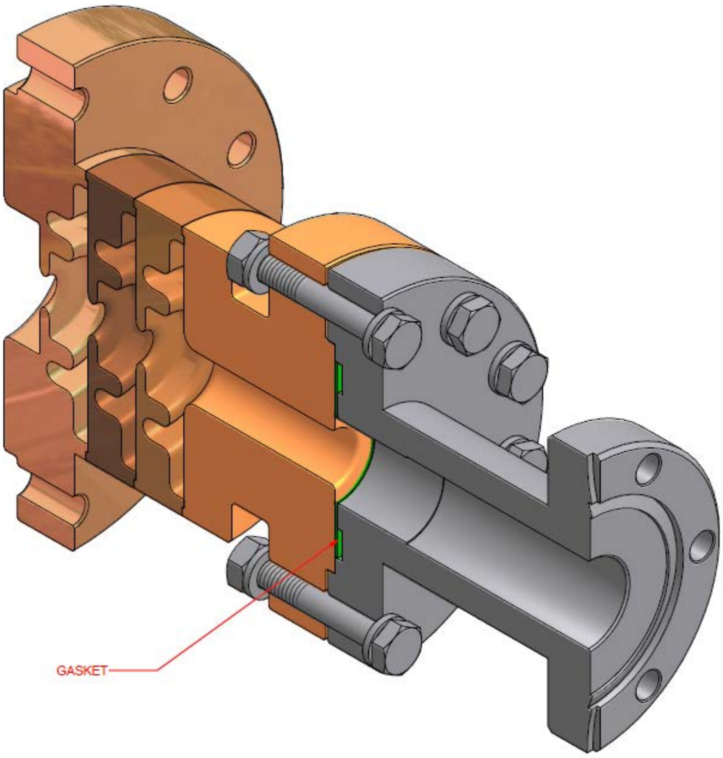

Figure 1 : Triple choke section solid model. In red it is shown the special gasket location.

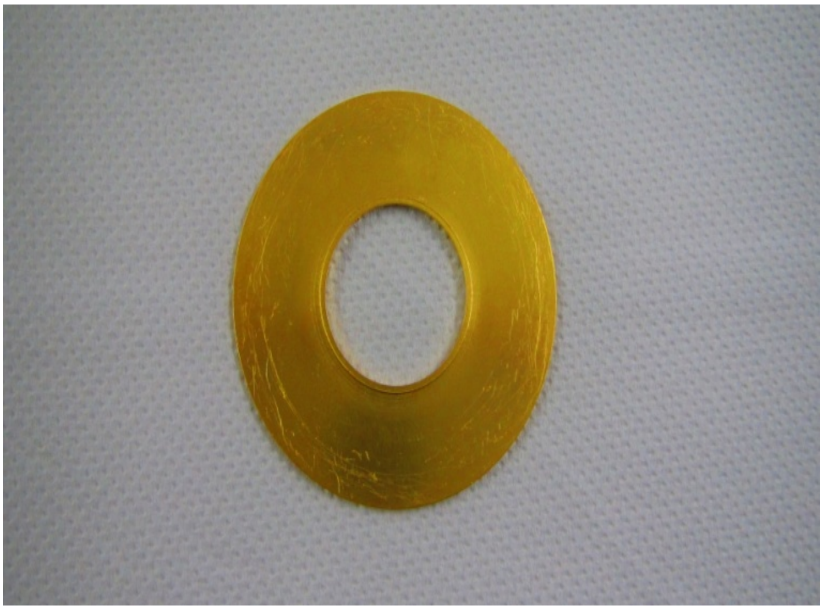

Figure 1a : Gasket of Figure 1 to separate vacuum and RF
joint to test hard alloy structures

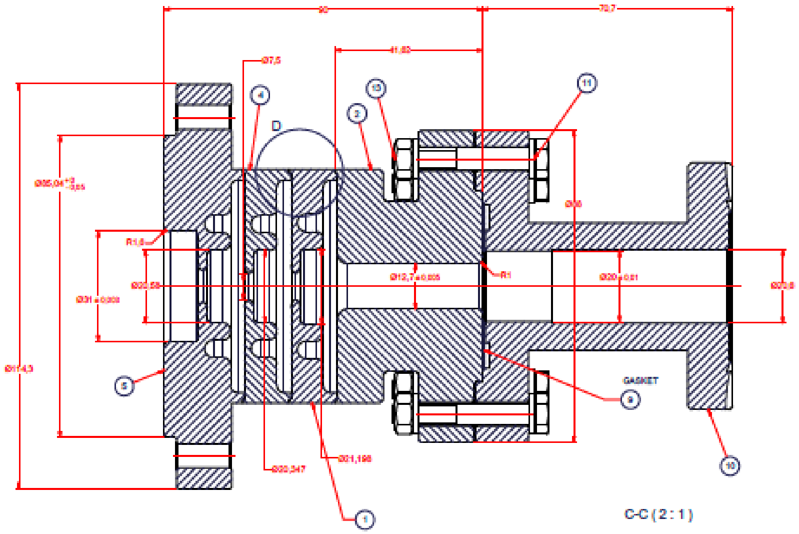

Figure 2 : Triple choke section mechanical drawing

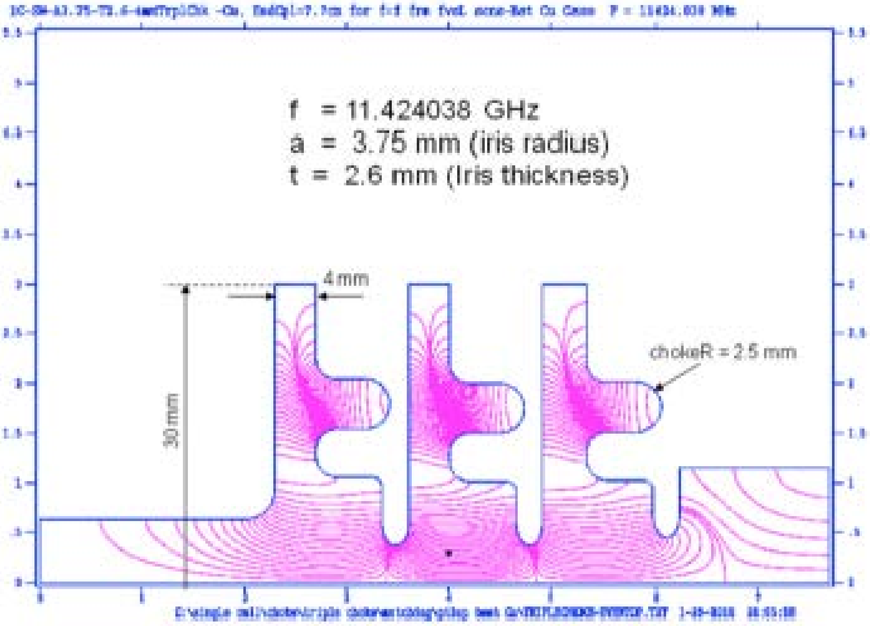

Fig. 3 : Electric equipotential lines of the triple choke section

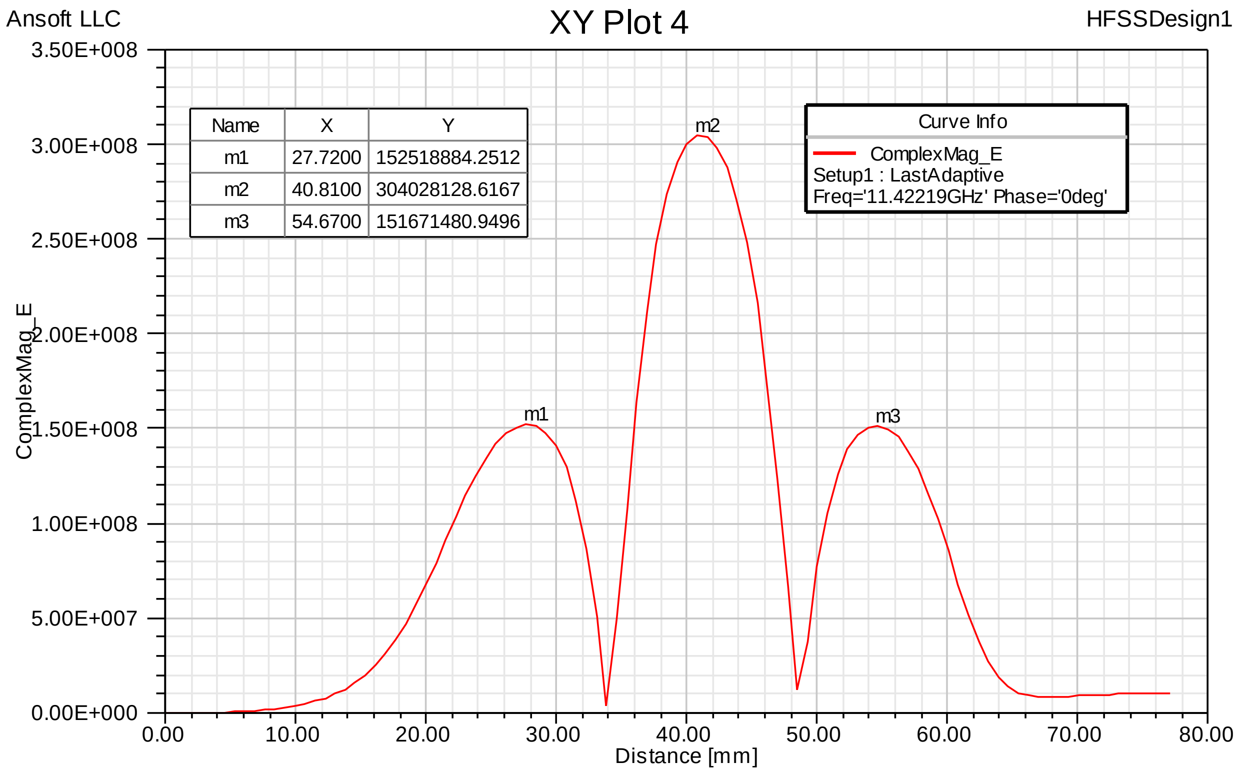

Figure 4 : Operating π mode on axis field profile

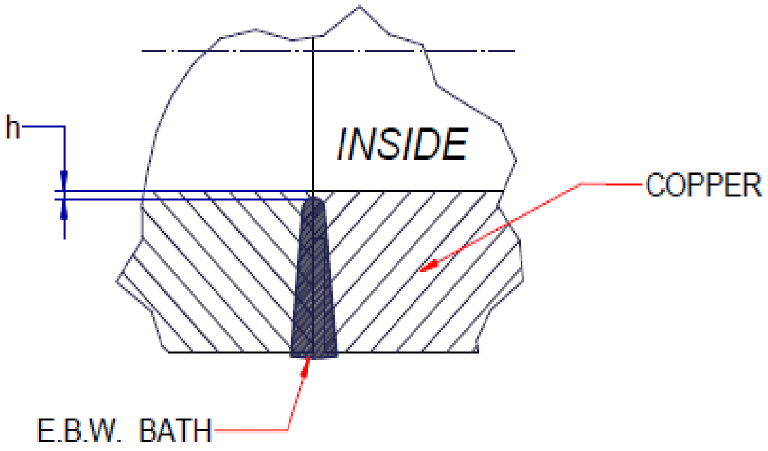

Figure 5 a: Welding region shape

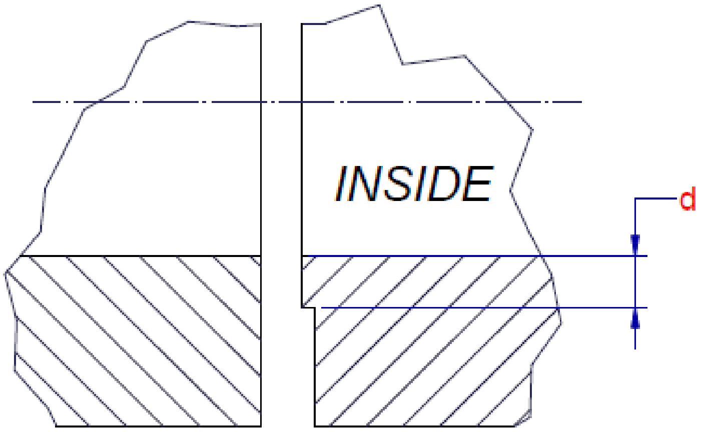

Figure 5 b: RF- joint shape between the contacting surface

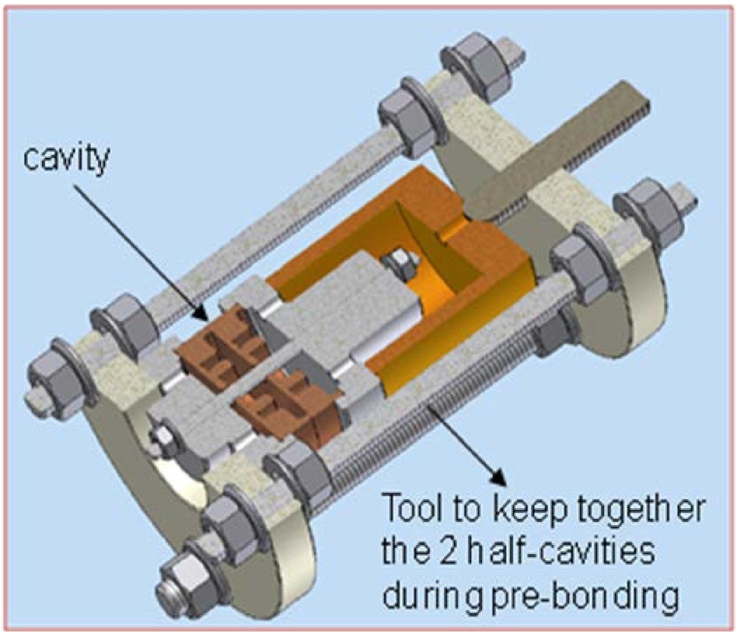

Figure 6: Solid model prototype cross section for testing the pre-bonding

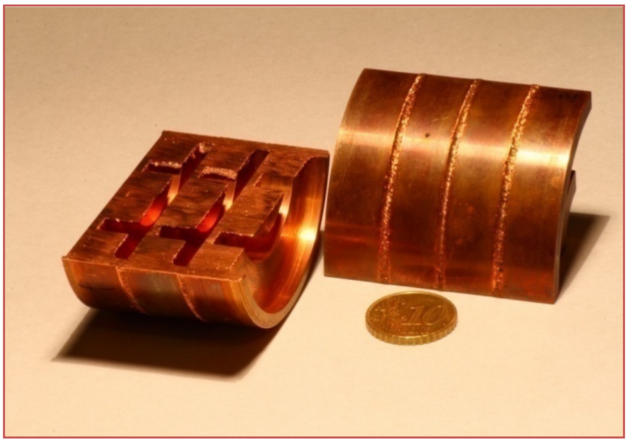

Figure 7a: Prototype cross section after the EBW process

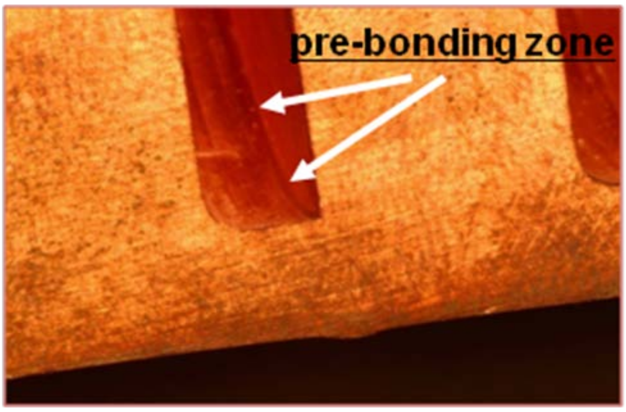

Figure 7b: Prototype cross section zoom after the EBW process shownig the prebonding zone

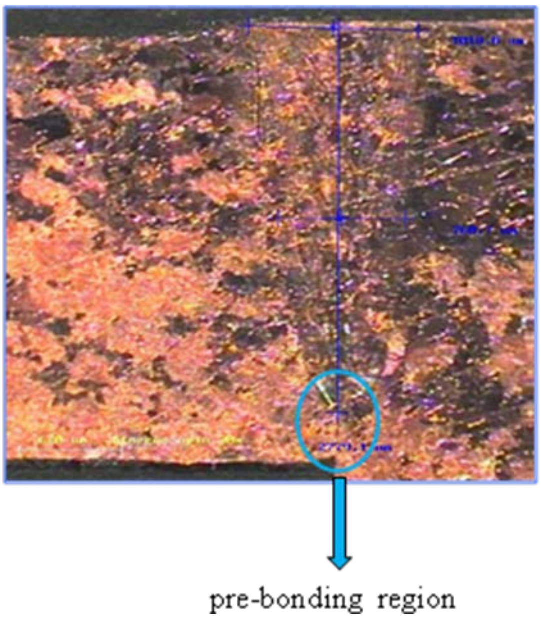

Figure 8: Welding region zoom of the prototype cross section after the EBW process

Figure 9 : Assembling of all cells for making the pre-bondig process

Figure 10: Single cavity

Figure 11: Devices after the pre-bonding process ready for making the E.B.W. process