CONSTRUCTION OF THE MODULES OF THE IFMIF-EVEDA RFQ

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Abstract

The IFMIF project aims to produce an intense neutron flux to test and qualify materials suitable for the construction of fusion power plants. We are working on the engineering validation phase of the project (IFMIF-EVEDA) [1], which consists on the construction of a linear accelerator prototype (LIPAC) to be installed and commissioned in Rokkasho (Japan). The RFQ is composed of 18 modules flanged together for a total length of 9.8 m designed to accelerate the 125 mA D+ beam to 5 MeV at a frequency of 175 MHz. The mechanical specifications are very challenging, tight tolerances are required on the machining and on the brazing process (Fig. 1). The line is subdivided into three Super Modules of six modules each. The production of the High Energy portion has been completed and delivered, while the Low Energy one is performing the acceptance test. They were commissioned to external firms. The production of the Intermediate Energy portion has been done in house (INFN) and will be fully commissioned soon. The first modules (16, 17 and 2) were produced adopting two brazing steps, while for all the remaining ones we adopted a single brazing step [2,3,4,5]. In this paper the production status as well as the development of the brazing procedure design will be described.

THE HIGH ENERGY SUPER MODULE (SM_III)

The SM_III contract was assigned by an international tender on April 2011 to an Italian firm (CINEL S.p.A.). The SM_III production has been a full scale completion of the Module prototyping. We optimise the geometrical survey versus the CuC2 components machining as well as the brazing tooling and brazing thermal cycle with a fruitful collaboration with the firm personnel. The extensive use of the CMM continuous active scanning represented the most effective tool for the milling cycle tuning and the most effective approach for the components assembly and module qualification at the acceptance stage.

An extensive FEM analysis was mandatory for the correct understanding of the material behaviour, for the tuning of the oven parameters and for the dimensioning of the brazing tooling components. The introduction of the TZM[1] (molybdenum alloy) springs helped a lot on the soft fixation of AISI parts, while minimizing the material budget during the brazing cycles. The SM_III production has been successfully completed on May 2014 (Fig. 2). The first two Modules (M_16 and M_17) have been brazed adopting a two-step process, while a single step brazing was used for the remaining ones, with all the advantages in terms of overall mechanical precision, costs and material properties deterioration.

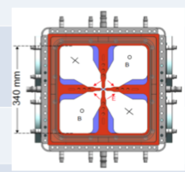
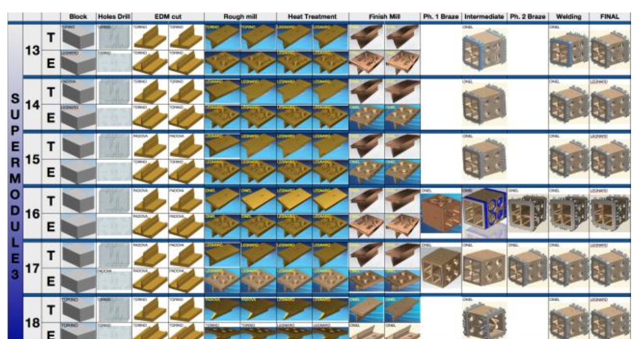
Parameter	Limit Value	Definition
Geometry of vane tip	± 10μm 	Overall error of position and shape of the modulation of the vane tip with respect to the electrode reference system, as defined in the drawings.
Roughness Ra	0.7 μm	For any sample measure on any surface being part of the cavity inner surface including the modulation on the vane tip (on a single electrode or on the module, after etching and passivation)
Vane tip position with respect to beam axis	± 50 μm 	Beam axis defined as the straight line going through the best fit points at the two ends of the module (w.r.t the mid planes of the four tips). The mid plane of the tip being defined by the two surfaces as indicated in the drawings.
Beam axis	± 50 um	Tolerance on distance between beam axis as defined above and the external references (small plates for supports and laser tracker reference)
Vacuum tightness of cavity and channels	10^{-9} mbar/l/s	Helium leak test of the cavity and all the channels
Pressure test of channels	5 bar	hydraulic test with dry inert gas

Figure 1: Geometrical Specification of the IFMIF-EVEDA RFQ.



Module	Limit Value	Pre-braze[MHz] fq(WG)	Post-braz[MHz] fq(WG)	Δf MHz/[μm]
M_16	± 50 μm	186.862	186.981	0.119/+17
M_17	± 50 μm	187.015	186.820	0.195/-25
M_15	± 50 μm	187.207	187.359	0.152/+22
M_18	± 50 μm	178.494	178.742	0.248/+35
M_14	± 50 μm	186.935	187.165	0.230/+30
M_13	± 50 μm	187.231		

Figure 2: SM_III production status (top); measured values of the overall frequency variations with respect to the nominal values (bottom).

The last part of the RFQ, where the RF power density is maximum, will be tested in Europe up to the operating field. A new test stand has been built at LNL, based on a 220 kW RF transmitter and of a dedicated cooling system (with separate circuits for vanes and external walls) for the

1 TZM ® –Titanium-Zirconium-Molybdenum Alloy (Plansee Group)

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control of the resonating frequency. The Modules M_18, M_17 and M_16, together with prototype 2 (used as end cell to close the RF field), for an approximate length of 2m, will be fed by one coupler, realized by INFN LNL (Fig. 3).

This RF test is very important to verify the functionality of RFQ, the alignment, the low power field tuning, the assembly, and the ability to reach the peak RF field, to master the RF power and to tune the resonant frequency. We shall try to identify all possible issues before the end of the module construction and before the transportation to Japan.

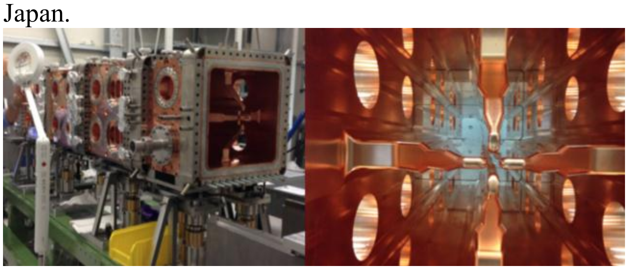

Figure 3: The Power Test Line (left); a view of the inner part of the PTL (right).

THE LOW ENERGY SUPER MODULE (SM_I)

The SM_I production was assigned by an international tender on June 2012 to a German firm (Research and Instrumentation Gmbh).

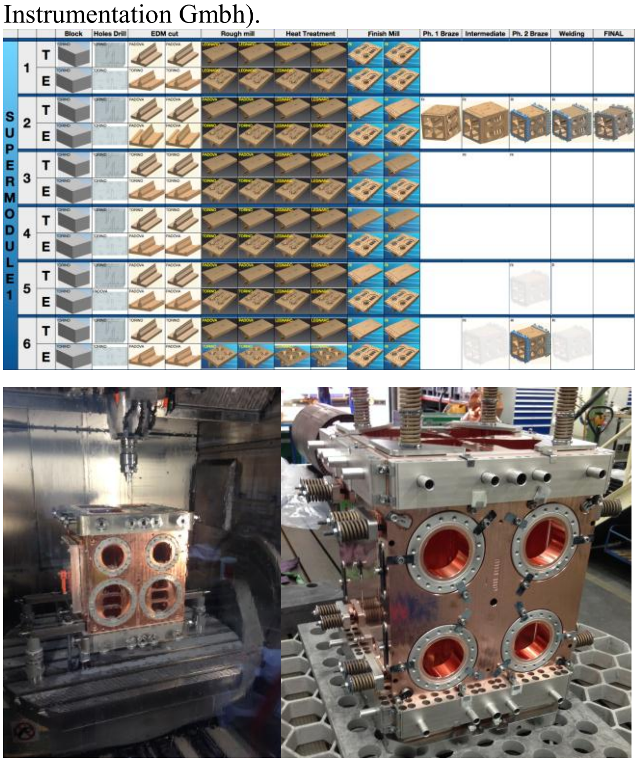

Figure 4: SM_I production status (top); Module 2 (bottom left); M_6 (bottom right).

They devoted a long time to finalize the milling processes with quite good results. They also acquired a Zeiss Accura with the continuous active scanning (as well as CINEL) and a new 5 axis milling machine, to cope with the overall project developed by INFN. The first Module brazed (M_2) was done with two step process to fix all the parameters of the design, while for the second one (M_6) they adopted the single step one, with excellent results (Fig. 4-bottom). The production has been seriously delayed (Fig. 4-top), but we are confident it will be completed by November 2014.

THE INTERMEDIATE ENERGY SUPER MODULE (SM_II)

The SM_II production started on May 2012 (INFN – Sezione di Padova). The electrodes belonging to this section have the most complex 3D geometry and consequently the milling process as well as the survey certification, result very time consuming. For these reasons we assumed to produce this section inside the INFN Sections of Padova, Torino, Bologna and LNL, providing also a back up solution for any problem occurring in the outsourcing contracts.

We adopted the single step brazing assembly for all the modules and we have brazed four about six Modules (Table of Fig. 5). We assume to complete the brazing of the two remaining Modules by October 2014, while the final milling will start September 2014 with Module 12.

Module	Tol.[µm]	Pre-braze[MHz] fq(WG)	Post-braz[MHz] fq(WG)	Δf MHz/[µm]
M_7	± 50 µm	188.140		
M_8	± 50 µm	188.425	188.661	0.236/+22
M_9	± 50 µm	187.882		
M_10	± 50 µm	186.945		
M_11	± 50 µm	186.550		
M_12	± 50 µm	186.117	186.323	0.206/+27

Figure 5: SM_II production status (top); measured values of the overall frequency variations with respect to the nominal values (bottom).

The brazing cycle has been carefully studied by means of thermo-mechanical FEM simulations, to predict the temperature distribution and stress induced on the CuC2 and AISI 316LN components. We tried to fit the temperatures measured on some thermocouples placed on the Module (Fig. 6: E's to T's joints and on the stainless steel components), with the ones simulated by FEM. We tuned consequently the emissivity data of materials at the different brazing cycle temperatures: Molybdenum for the reflecting screens of the oven; CuC2 and AISI 316LN for the RFQ components.

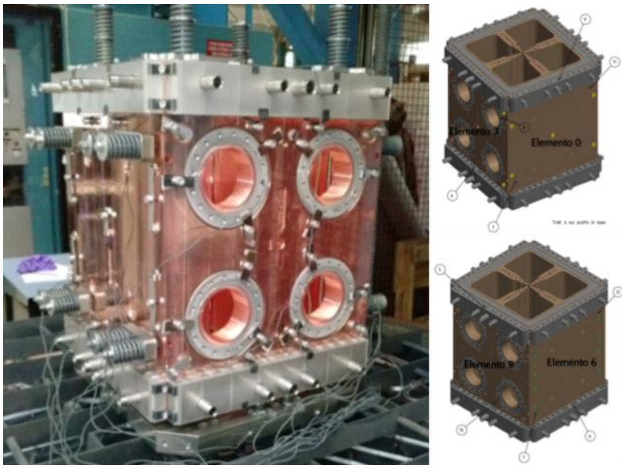

Figure 6: The M_12 before the brazing cycle (left); the thermocouples position and number.

The close definition of the material emissivity (ε_i) needed an interactive FEM simulation work in particular for the molybdenum reflecting screens [5] and for the CuC2 elements. The values adopted for all the materials are reported (Fig. 7). We used the $\varepsilon_{\text{(CuC2, oxidized)}}$ value until 250 °C, an $\varepsilon_{\text{(CuC2, extrapolated)}}$ value above 400 °C and a linear interpolation of the two in between. The $\varepsilon_{\text{(CuC2, extrapolated)}}$ value was obtained by fitting the temperatures measured on thermocouples, with the FEM simulated ones, during the final rump up (from 800 °C until 890 °C), where the 'liquidus' temperature of the Palcusil 10[2] alloy is reached.

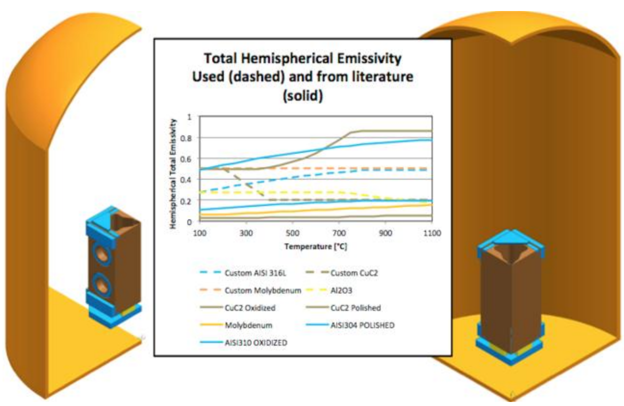

Figure 7: The Ansys FEM model of the Module in the brazing oven (sides); Table of the emissivity for the materials used at the brazing cycle temperatures.

The thickness of the Module vanes varies from 80 mm until 30 mm along the RFQ cavity line, while the vessel wall thickness remains constant. The FEM analysis for the brazing cycle was consequently performed for two types of geometry: the low and high energy Modules. We need to estimate the differential heating up and the components elongations, to avoid that any embedded differential deformation arise. We want to minimize the differential displacements between the E's and T's components (due to their different view factor and thermal capacitance), before the interference between the front flanges and the copper elements occurs.

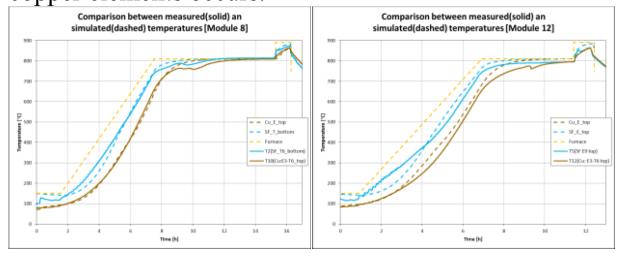

Figure 8: Comparison between the thermocouples data and the FEM simulation for low energy (left) and high energy Module geometry (right).

An intermediate plateau at 650 °C was conservatively introduced (Fig. 8) for the low energy Modules (M_7 until M_10), while it is not strictly needed for the high energy ones (M_11 and M_12).

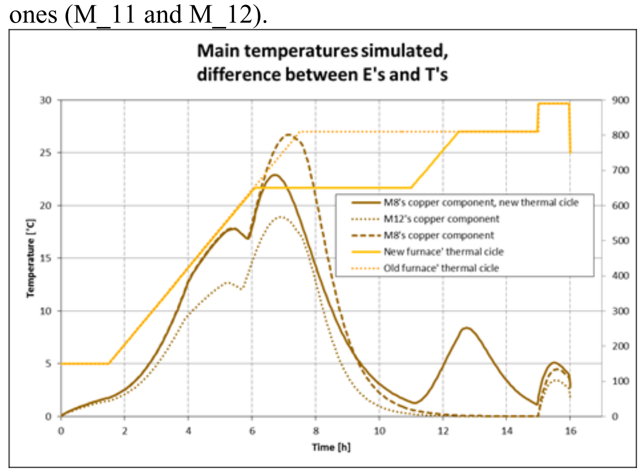

Figure 9: FEM simulated differential Temperature between components, considering an intermediate plateau (continuous line) or without (dotted line).

We defined so far a very accurate instrument for a precise estimation of the temperature distribution during the brazing cycle for even very complex geometry of the assembled parts (Fig. 9).

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2 Palcusil 10: 59% Ag, 31% Cu, 10 % Pd, liquidus temperature: 852 °C, solidus temperature: 824 °C.

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