DESIGN AND FABRICATION OF THE ESS-BILBAO RFQ PROTOTYPE MODELS

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Abstract

As part of the development of the ESS-Bilbao Accelerator in Spain, two different sets of radio frequency quadrupole (RFQ) models have been developed. A set of four oxygen free high conductivity copper weld test models has been designed and manufactured, in order to test different welding methods as well as other mechanical aspects involved in the fabrication of the RFQ. A 352.2 MHz four vane RFQ cold model, 1 meter in length, has also been designed and built in Aluminum. These models serve as a good test bench to investigate the validity of different finite element analysis (FEA) software packages. This is a critical part, since the design of the final RFQ will be based on such simulations. The cold model also includes 16 slug tuners and 8 coupler/pick-up ports, which will allow the use of the bead-pull perturbation method to measure the electric field profile, Q-value and resonant modes. In order to investigate fabrication tolerances, the cold model also includes a longitudinal test modulation in the vanes, which is similar to the one intended for the final RFQ. In addition, it represents a useful tool to explore the influence of the modulations in the electromagnetic design.

OHFC WELD TEST MODELS

A set of four oxygen free high conductivity copper *Weld Test Models* (WTMs) has been designed and manufactured, in order to test different welding methods (electron beam, laser and vacuum brazed welding) as well as other mechanical aspects involved in the fabrication of the RFQ (see Fig. 1).

Vacuum brazing offers some remarkable advantages: it is commonly used and well-proven technique; the resulting Q is high; and many joins can be made in one hit. Nevertheless, expertise and experience are a must. It also requires dedicated equipment, and customized machining ops are required to minimize distortion at braze stage.

The Laser welding technique has some advantages over vacuum brazing: since a narrow weld in region is required, this results in a smaller heat affected zone; vacuum is not required during brazing; and it is possible to dismantle by machining away the shallow weld. On the other hand, the list of shortcomings is long: access for the laser head is limited, resulting in the significant overhead of manufacturing

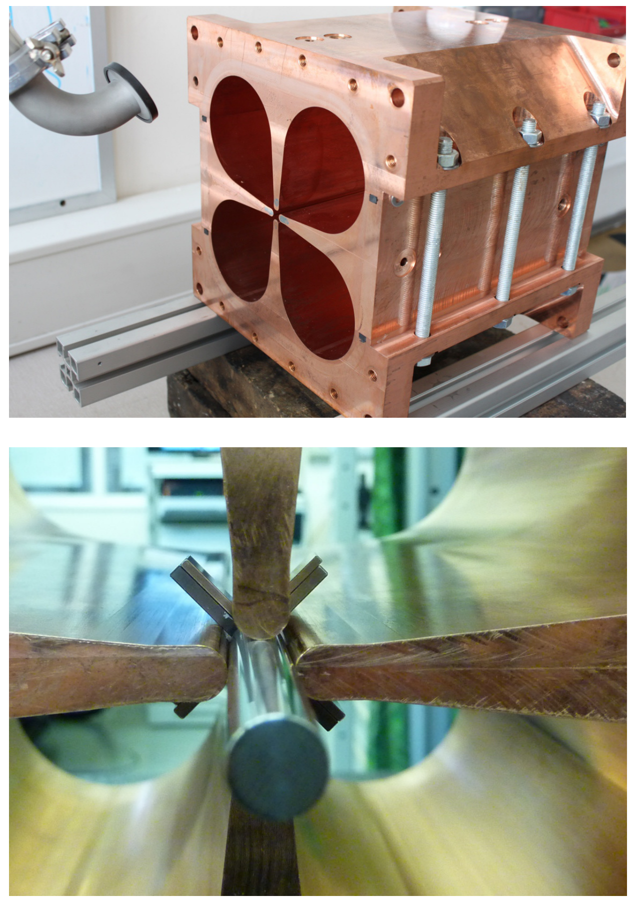

Figure 1: **a:** Assembly of one of the WTMs —machined at *Swisslan*— at the Imperial College London. Different vacuum tests have been performed on this model. **b:** Detailed view of the ancillaries used for the metrology of the vacuum brazed test.

a custom laser head; copper is a poor material to laser weld due to high reflectivity and conductivity; and the technology is relatively new, making expertise rare.

In the case of Electron beam welding, it is a mature technology that allows a full penetration weld from the outer walls of the RFQ, avoiding access problems. Nevertheless, beam exit is ragged, so features inside the RFQ have to be protected from the electron beam. Also, a larger heat zone is affected than in the laser technique and a large vessel is required to keep the whole process vacuum tight.

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Finally the O-ring[1] technique's success is based on its simplicity: since no heat is applied, no distortion occurs, it is very low cost and is easy to dismantle and clean if required. The corresponding drawbacks are a lower Q-value and the potential for vacuum leaks over time due to the non-permanent join.

Conclusions

As predicted, vacuum brazing model test showed unacceptable alignment distortions [1]. The O-ring model test demonstrated the feasibility of assembly and vacuum tightness of this method: it was selected for the FETS project [2] in order to allow the RFQ to be dismantled. Test plans for laser and e-beam weld were postponed in time due to budget limitations.

ALUMINUM COLD MODEL

A 352.2 MHz four vane RFQ cold model, 1 meter in length, has been designed and built in aluminum (see Fig. 2). It serves as a good test bench for obtaining experience in four main different areas: the validity of finite element analysis (FEA) results, the optimum machining process to achieve the required mechanical tolerances, knowledge of alignment of the four vanes and the various field measurement methods.

The validity of different FEA software packages is critical, since the final RFQ design will be based on such simulations: both the the structural mechanical analysis and the physics simulations, such as beam dynamics and RF.

In order to investigate fabrication tolerances, the cold model also comprises a longitudinal test modulation in the vanes, which is similar to the one designed for the final RFQ. The search for a company which can machine the necessary tolerances has been another motivation in fabricating the cold model due to the complexity of the geometrical form.

The combination of two different machines —*5 axis mill* and *boring machine*— proved superior, with machining carried out in 4 steps: (1) Rough milling. In this stage 5-6 mm have to be left for each coat. The most important things are the control of the milling zone temperature and the clamping operation, in order to avoid linear or torsional deformations generated by temperature gradient or by the clamps (see Fig. 2a). (2) Stress relief heat treatment. Heat treatment to relieve internal stresses. (3) Pre-finish. Finish the less important parts of the piece and prepare the important faces to finish. (4) Finish. High precision finishing all the functional faces (the modulation and the lean faces).

In the two last steps the most important things are the control of the room temperature and in particular the clamping operation. It is vital not to generate deformations during clamping and avoid thermal deformations in order to obtain a high precision piece. In the RFQ cold model the alignment of the four vanes is achieved with 8 pins, with a position tolerance of $\pm$ 0.01 mm. If alignment using these pins alone is not sufficiently precise, further alignment will be carried out with a tridimensional machine.

[1] Vacuum sealed with a polymeric gasket and bolts for mechanical joining.

Figure 2: a: Major vane during machining phase,after first rough machining at *Mecanizados Mandrinados Mancisidor*. b: Same vane at the *Zeiss* metrology lab.

Electromagnetic Design

Design Specifications The specifications imposed on the design of the RFQ Cold-model can be summarized as: 1) Field flatness. The absolute electric field along the RFQ for the fundamental mode must be as constant as possible. 2) Fundamental frequency mode separation. The fundamental resonant quadrupole mode must be close to the final operating frequency (352.2 MHz), with the dipole mode separated by at least 4 MHz. 3) Modulation tolerances. The Cold-model is required to include modulation in order to test fabrication accuracy. 4) Frequency tuning. Slug tuning rods will be inserted in order to obtain fine adjustment of the RFQ resonant modes.

Particles require very specific and constant field conditions. The accelerating $\bar{E}$ field must be as flat as possible along the total length of the RFQ and no field zeros can be present. In the case of the RFQ, the fundamental quadrupole mode (TE_{210}) is the one used for acceleration.

It is very important to isolate this fundamental mode from: On the one hand, the rest of the quadrupole modes (TE_{21n} with n$\geq$1). On the other, the dipole modes (TE_{11l}) not to disturb the required field characteristics.

Radial Matchers and Field Flatness It is important to remark that the total length of the cavity has been fixed to 1 m due to machining limitations and hence, the only way to isolate the fundamental mode from the rest of the modes

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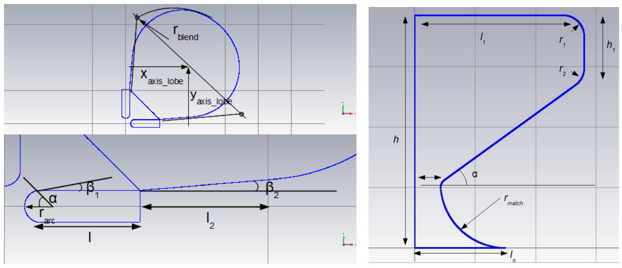

Figure 3: a: 2D layout of the matcher. b: 2D of the lobes parametrisation.

is by varying the cross-section geometry (see Fig. 3a) or adjustment of the RFQ endings. Once this goal is achieved, the following step is to obtain field flatness for the TE_{210} fundamental mode.

In the 1 m model, a “Bulbous bow” shape is used (see Fig. 3b) at both ends with the corresponding input and output radial matchers. Both matchers have a radius of curvature of r_{match}=21.56 mm. The whole design process involving the geometrical parametrization of the cross sections, lobes and radial matchers is done for a model of RFQ with no modulation included since it requires a recursive parametric study involving many variables (see Fig. 3) and therefore becomes a very time consuming task. Finally, a representation of vane profile is embedded to test the precision in the fabrication process and gain experience in 3D design and simulation. The final modulated model is set to a working frequency for the quadrupole mode of 343 MHz, with dipole modes at 333 MHz. This 10 MHz shift exceeds the specification of Δf>5 MHz. A more detailed explanation of the procedure is given in: [3].

Tuners 16 slug tuning ports have been added to the cold model in order to test the tuning range of the measured Aluminum prototype, as compared to the results obtained from electromagnetic simulations [6]. It is also important to be able to test the control systems in real time: Small variations in the cavity volume induce variations in the magnetic and electric field producing small shifts in the resonance frequency.

The chosen design uses 16 tuning rods (Ø40.75 mm) placed in a similar way to those in the final RFQ segments. This diameter has been chosen as it matches the diameter used for the N-type RF power couplers. As such, it will also be possible to inject RF power at the same location. Each tuner enters perpendicular to each of the RFQ lobes. The cavity has been designed to operate at a slightly lower frequency and increase its resonant frequency by introducing the metal rods in the cavity. Nevertheless, tuner position limits required to compensate for given construction errors may be derived from inter-vane capacitance errors and intensive work must be done in this way in order to fix the exact position and penetration of the slug tuners in order not to affect particle acceleration [4].

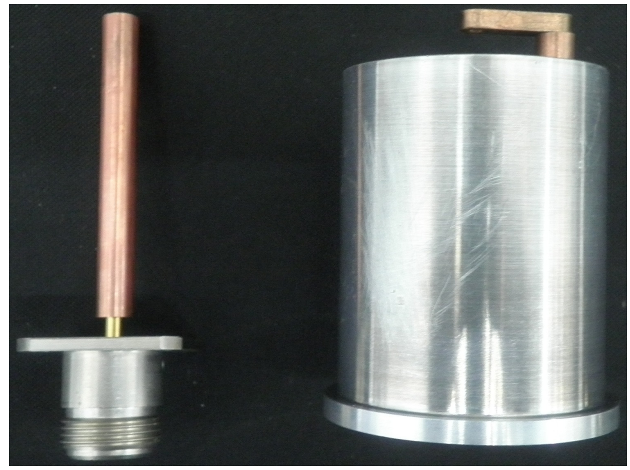

Figure 4: RF coupler

Couplers Since the Cold-Model has to be excited by an RF signal, RF power couplers were designed accordingly (see Fig. 4) [5]. Ports have also been added to the model in the areas where the magnetic field turns around the vanes in order to ensure proper coupling. The couplers are coaxial N-type with a simple wire loop and diameter of 40.75 mm.

Future Work

The Cold-model will go through metrology tests in a tridimensional machine, focused in the modulation part. The results, will then be compared with the designed modulation to approve the selected machining process. Once this stage is completed, an assembly and alignment process will follow. Finally , the model will be thoroughly characterized. Specifically, the intrinsic parameters such as the resonant frequency and the quality factor, as well as the electromagnetic field profiles obtained by means of bead-pull technique [6, 7].

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