THE MANUFACTURE AND ASSEMBLY OF THE FETS RFQ

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Abstract

The Rutherford Appleton Laboratory (RAL) Front End Test Stand (FETS) uses a 324 MHz 4-vane Radio Frequency Quadrupole (RFQ) to accelerate H- ions from 65keV to 3MeV. The RFQ is a copper structure that has been designed as 4 nominally one metre long assemblies. Each assembly consists of 2 major vanes and 2 minor vanes that are bolted together and sealed using an O ring. The mechanical design for the FETS RFQ is complete and the manufacture is underway. In order to achieve the designed physics performance the vanes must be machined and assembled to high degree of accuracy. This requirement has demanded a tight synergy between the design, manufacture and metrology services. Together they have developed detailed procedures for the manufacturing, inspection, alignment and assembly phases. The key points of these procedures will be detailed in this paper.

INTRODUCTION

The precision required to produce a 4 vane RFQ that delivers a high beam transmission at high current is close to the limit of what is possible to manufacture and measure using the technology available today.

During the engineering design phase various manufacturing techniques were investigated including having custom extrusions made to minimise waste. The manufacturing method selected was to machine the RFQ pieces from solid billets of copper. Despite the large amount of material waste, at nearly 80% in the case of the major vane, this method was calculated to be the most cost effective with the additional advantage that the techniques employed were tried and tested during the cold model manufacture. During the engineering design phase the FETS team liaised with the manufacturing, metrology and the alignment teams to ensure that design features were incorporated that would improve both the manufacturing and the alignment processes.

This paper describes the manufacturing operations employed to minimise material distortion and highlights the key datums and the tolerances used including how those tolerance values were determined. The vane to vane alignment technique required to produce a one metre RFQ section is described along with the technique for aligning the assembled RFQ sections to the FETS beam-line.

MANUFACTURING

To ensure flawless machining of the RFQ vanes 3D IGES CAD models were supplied to the manufacturer [1] in addition to traditional 2D engineering drawings. The 3D models were used to define the vane tip modulations for the CNC machining operations.

At the outset of machining it was not known how much the material would distort as the internal material stresses induced by the material forming processes were relieved by the removal of material. For this reason the first billet was machined flat on one side and then rough machined to +10mm on the vane side to enable the distortion to be measured. The resulting distortion was measured at a surprisingly low 0,010 to 0,015mm. High temperature stress relieving was avoided to preserve the mechanical properties of the copper. Instead the internal stresses were managed by performing two roughing operations, on alternating sides, each separated by several days to allow the material to relax. The machining operations were divided into separate zones: the outside face which includes a vacuum port and cooling channels; the 45 degree faces which include the tuning ports; the end faces and the vane profile. Each zone was machined to +10mm before allowing the material to relax. The next stage was to machine each zone to +2mm. Negligible material deformation was found at any stage. The stock material was hot rolled grade C10100 Copper supplied by Metelec Ltd [2]. Figure 1 shows one major vane and one minor vane being rough machined on the end faces using a Soraluce 4 axis milling machine.

Figure 1: RFQ major and minor vanes being machined.

Before final machining could begin cutter trials were performed to discover the most suitable cutter profile and composition along with the optimum machining speeds and feeds. To minimise RF breakdowns a high quality surface finish of less than 0,8 microns average surface roughness is required. To ensure that no surface irregularities are present as a result of a tool change it is a requirement that one tool lasts for an entire 15 hour vane surface machining operation. Five cutters were trialled by the manufacturer under guidance from Emuge Ltd [3] and the coated high helix angle cutter designed to machine aluminium delivered the best finish with acceptable wear.

A second machining operation is required on each assembled and aligned RFQ section. This operation can be split into two tasks. Firstly, to fit and machine dowel blocks that fix the vane to vane location. Secondly, to create the high tolerance flat and coplanar end faces required to achieve a good RFQ section to section vacuum seal. This will allow an RFQ section to be dismantled, which is necessary to fit the 3D O ring vacuum seal, and then reassembled to the original aligned dowelled position [4]. The RFQ vanes could not be aligned during the initial assembly with the vacuum seal in place due to the large frictional forces that are created when compressing the Viton O ring.

Datums

The main datums for both the major and minor vanes are two external jig bored dowel holes on the outer face. Together the holes define the axis of orientation for the vane tip and provide an external reference that is always accessible. Furthermore, the position of the upstream hole acts as a reference to the start point for the vane tip modulations which aids longitudinal vane to vane alignment. The hole pitch remains constant across all four variable length RFQ sections to allow the use of one jig for all of the manufacturing. The manufacturing jig is a 30mm thick ground steel plate.

Tolerancing

In broad terms the exterior surfaces and features of the RFQ require manufacturing to standard engineering precision whereas the interior surfaces require manufacturing to extremely high precision. In order to understand how the machining tolerances would affect the RFQ performance we first had to understand the sensitivity of the RFQ, namely its resonant frequency and beam transmission, to deviations in size, shape and alignment away from the theoretically perfect model. This is where the FETS RFQ design process becomes invaluable: 3D CAD models of the vane tips are produced by a custom script within Autodesk Inventor that uses the vane modulation parameters produced by RFQSIM [5]. Together these CAD models were used to create an assembly of each RFQ section which were altered to represent real world machining imperfections and assembly misalignments. Those models were imported into COMSOL [6] and CST MWS [7] to determine the RF properties [8] and 'real' field distributions. Those field distributions were then used to track particles through the distorted RFQ model using GPT [9]. It is beyond the scope of this paper to detail the findings from these simulations but in short, the RFQ is the most sensitive in the region of the vane tips, the alignment of which is a function of both the machining quality of individual parts plus the position and form quality of the interfaces. Table 1 highlights the main tolerances required during the manufacture of the major and minor vanes.

A profile tolerance was used to describe the 3D vane tip modulation. The transverse profile is controlled by the tolerances shown in table 1 and the longitudinal vane modulation is controlled by a profile tolerance of 0,02mm.

Table 1: Main RFQ Part Manufacturing Tolerances

Region	Value (mm)	Feature being controlled
Interface planes	0,01	Vane tip alignment
Vane tip	0,02	Vane tip precision
Quadrant radius	0,05	RFQ frequency

METROLOGY & ALIGNMENT

Inspection of the individual vanes will be made at the manufacturer using an articulated arm portable coordinate measurement machine (PCMM). This will confirm that the parts have been machined to the specification. Further inspection of the vanes will be made at RAL by the metrology department using a conventional CMM to verify the manufacturer's measurements and as an information source that can be referenced in the unlikely event of the RFQ performance being sub-optimal.

Vane to Vane Alignment

The vane to vane assembly and alignment will be performed in collaboration with the RAL metrology department. The base major vane will act as the fixed datum to which the remaining vanes will be aligned. An alignment jig that can be fixed to each end of the base major vane has been designed and manufactured, see Figure 2. The jig contains high precision dowel holes that mate to the datum dowel holes of the minor and major vanes. Each vane will be added and aligned in turn. A removable central guide for tapered dowels acts as a check for the alignment in the critical region of the vane tips.

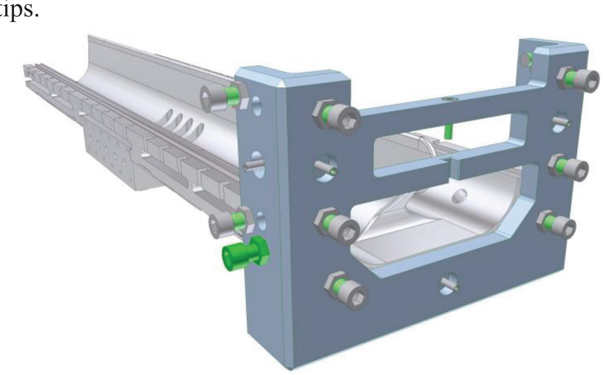

Figure 2: Jig used for RFQ vane to vane alignment.

Both minor vanes and the top major vane have horizontal translation and horizontal rotational degrees of freedom only. The vertical separation of the vane tips is controlled entirely by the machining tolerances and hence the tightest tolerance is for the minor vane interfaces where both the size and form must be controlled to 10

ISBN 978-3-95450-115-1

micron precision. A simplified exploded view of the vane to vane assembly is shown in Figure 3.

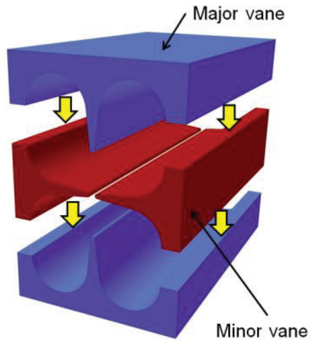

Figure 3: Simplified exploded view of one RFQ section.

When the physical alignment is complete a bead-pull test will be performed to measure the cavity modes and this will highlight any machining or alignment asymmetries. A dedicated bead-pull / RF test flange has been designed to act as a precision guide for the bead line and to compensate for the lack of vane cutbacks at the RFQ section to section interfaces, see Figure 4.

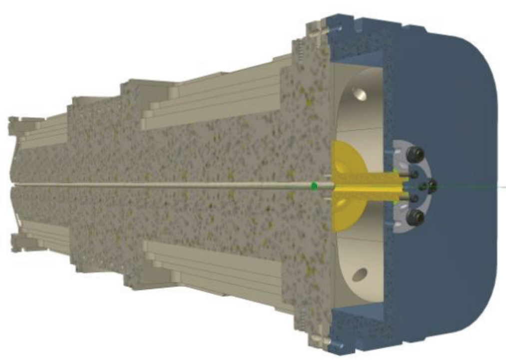

Figure 4: Section view of bead-pull / RF test end flange.

Further bead-pull test will be performed with the RFQ tuners [10] in position to measure the longitudinal field flatness. The tuners will be shimmed to temporarily set the correct length to provide a flat field before being machined to fix that determined length. In addition to the bead-pull test a low power RF test will be performed to determine the depth of the longitudinal field flattening grooves in sections 2, 3 and 4 [11]. After this stage RAL metrology will measure the assembled RFQ section 'clover leaf' profiles. This set of measurements will enable us to check the alignment following the second stage assembly with the vacuum seal in place. Once assembled there will be very limited access inside the RFQ for the purpose of measuring. For this reason the majority of interior measurements will have to be inferred from a composition of the individual vane measurements.

RFQ Section to Beam Axis Alignment

Each assembled one metre section of RFQ must be lifted in its cradle onto the adjustable mounts of the test stand. The ISIS alignment team will use custom made optics that fit into the conical bore of the RFQ to align it to the beam axis. The external manufacturing datum holes can be used to cross check the position. In addition the external datum surfaces will be used to control the RFQ transverse rotation. The individually aligned RFQ sections will be bolted together end to end. An intermediate flange between the sections completes the vacuum sealing mechanism and holds the vane ends at their calculated separation of 0,2mm. Electrical contact in the region close to the vane tips is maintained by the inclusion of a longitudinal beryllium copper spring.

Simulations have been performed to study the effect of offsetting an entire one metre RFQ section from the beam axis. The first results indicate that beam transmission and emittance growth are acceptable even with an offset of 100 microns. The FETS team are confident of alignment to approximately 20 microns.

OUTLOOK

The manufacture of the FETS RFQ is progressing well. All sixteen pieces are machined to +2mm and the trials to discover the optimum finishing cut parameters are complete. The assembly and alignment procedure to be followed is understood and documented. The manufacture of the RFQ ancillary components including the tuners, cooling baffles, end flange and RF test end flange assemblies is well advanced. The design of lifting and handling fixtures is underway. The experience gained from assembling, aligning and installing RFQ section 1 during the Summer of 2012 will be fed back into the design before proceeding to finish machine RFQ sections 2, 3 and 4.

ACKNOWLEDGEMENTS

The authors would like to thank Mr Tim Smart and the manufacturing team from N.A.B. Precision Tooling Ltd for their close cooperation with the FETS team, without which the successful manufacture of the RFQ would not be possible.

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ISBN 978-3-95450-115-1