EXPRO High Power W-Band Traveling Wave Tube

Contract 4000119380/17/NL/HK/hh "High Power TWT"

Executive Summary

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1 Introduction

This report provides a high level summary of the activities undertaken, the outcomes achieved and the issues encountered under Contract 4000119380/17/NL/HK/hh “High Power TWT” with the objective of developing a breadboard High Power W-Band Traveling Wave Tube.

The project was undertaken as a collaboration between Strathclyde University (lead and design of microwave system, non-linear simulations, microwave measurements) TMD Technologies (design of the electron gun, PPM focussing system, build of breadboards) and RAL Space (primarily the fabrication of the delay line components using their unique machining capability).

2 Design of the interaction waveguide

Various options were considered for the interaction waveguide. Helix and related technology were discounted since it was felt that the sizes were already extremely challenging in the Ka band, and scaling to significantly higher frequency was unattractive. Coupled cavity type approaches were considered but would not be consistent with the ESA targets for bandwidth required for communication applications and would likely be difficult to machine and join the delicate detailed structures at such high frequency. A range of alternative schemes were therefore considered. Metamaterials show promise as do a range of interdigital and comb schemes – however these are relatively undeveloped and brought high risk for a number of different reasons. Folded waveguide methods seemed likely to offer the power and bandwidth required for the communications applications and therefore work focused on this method. It brings the attractive feature of allowing machining in two halves using precision milling – this could eliminate aspects of the uncertainty which tends to impact helix type designs, in unit to unit reproducibility since it would remove one aspect dependent on skilled artisan work – the build of the delay line. The geometry of the delay line is shown in Figure 1

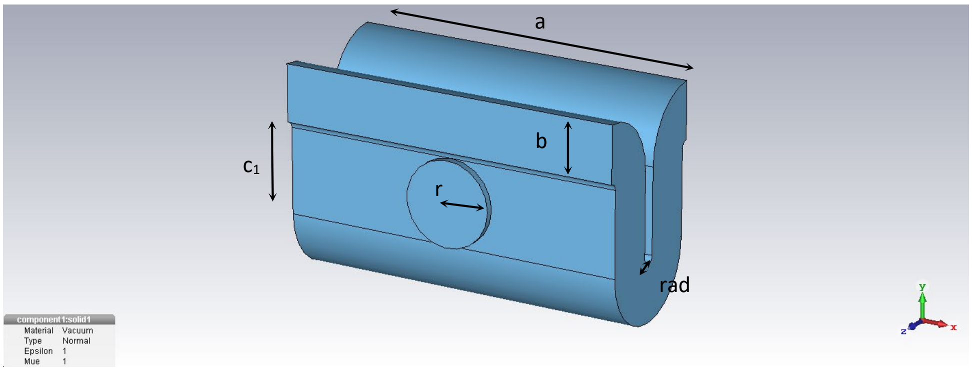

Figure 1: a = long waveguide dimension or “width”, b = short waveguide dimension “height”, c = vertical waveguide dimension, rad = waveguide radius and r = beam tube radius, reproduced here for convenience.

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The dispersion was calculated using analytical approaches to provide synchronism with a 14.5kV, see Figure 2, electron beam. This dispersion was validated in full wave modelling (both frequency and time domain approaches) which identified the very narrow stopbands introduced by the presence of the beam pipe – required to transport the beam and which presents a periodic loading of the delay line.

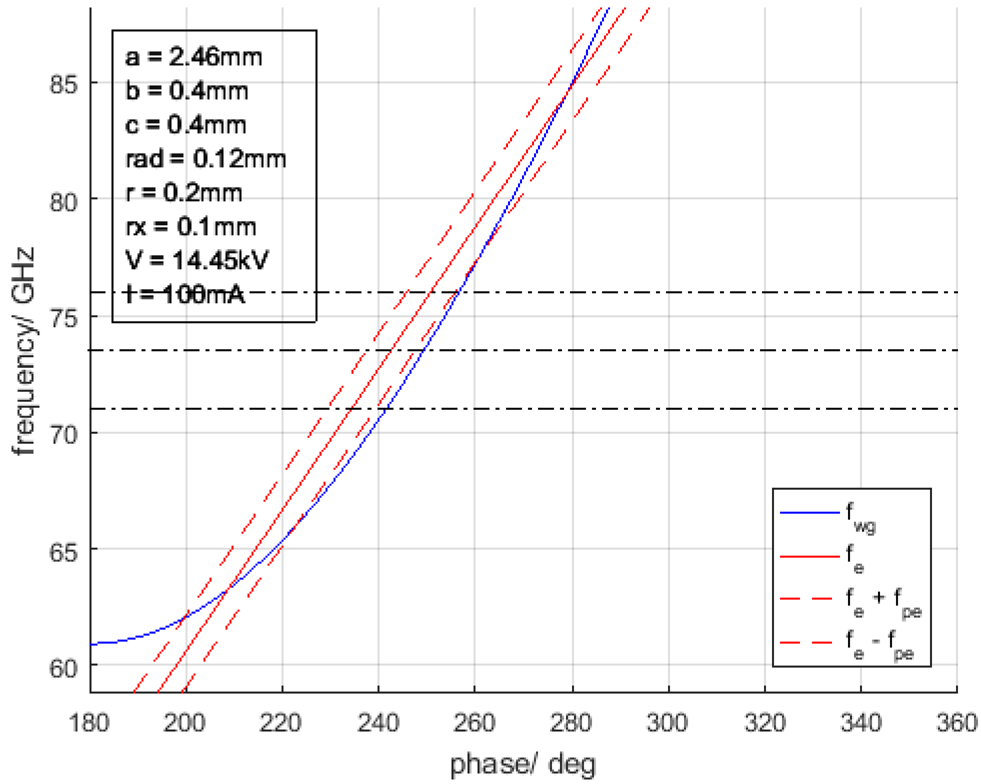

Figure 2 Analytical dispersion curve for the SWS with modified dimensions for higher beam voltage, shown here are the 1st space harmonic, the beam line and space charge waves.

The dispersion predictions from the simulations was validated with three test vehicles manufactured in two halves. The dispersion of a single period was extracted by a differential measurement and overall dispersion was matched with a long structure representative of the actual delay line for the TWT. The test vehicles and comparison with prediction are shown in Figure 3 and Figure 4. This validation allowed the project to proceed with non-linear simulations of the TWT performance.

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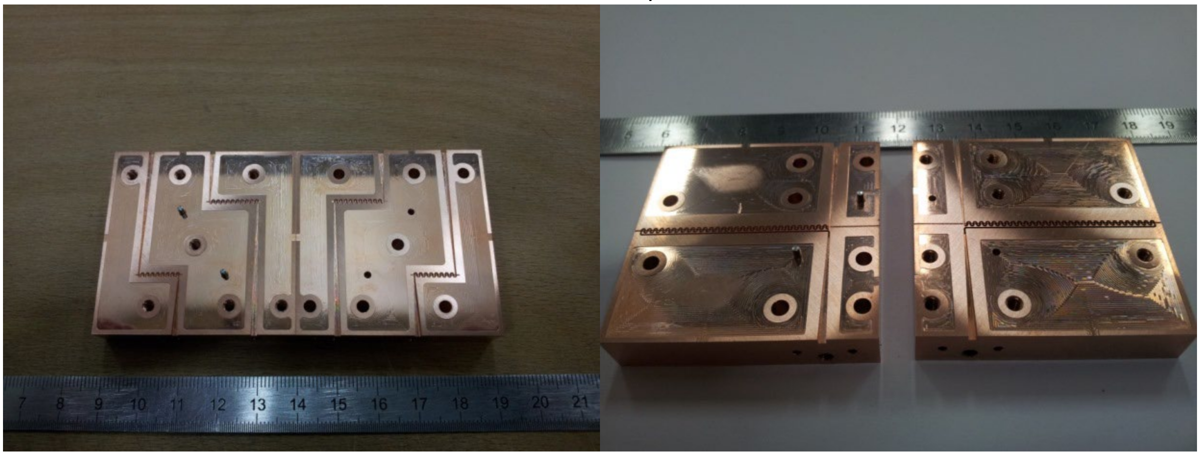

Figure 3 Finished test vehicles, model-1 (LHS) with two SWS (8 – 10 periods) and model-2 (RHS) long section of 30 periods along with extended waveguide runs.

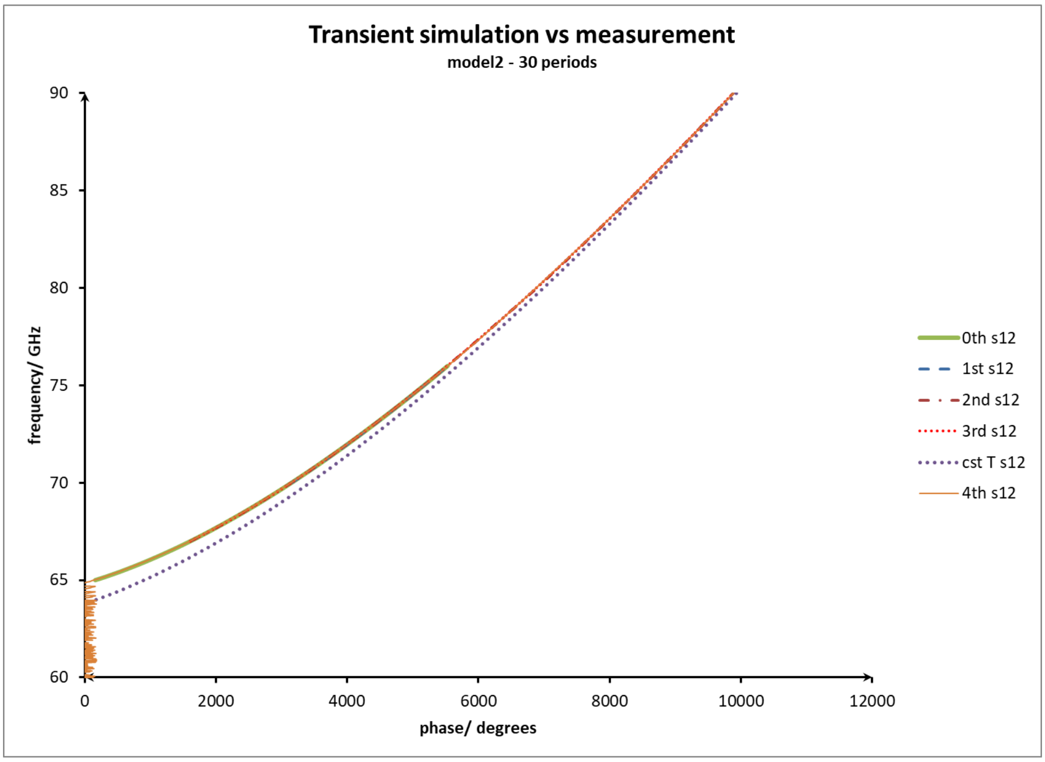

Figure 4 Comparison between three separate measurements of 30 period model-2 and the transient phase result from the CAD model (note there remains a residual integer 360 degree offset hence the waveguide is NOT cut-off at 0 phase shift shown here)

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3 Predictions of non-linear simulations

Non-linear simulations were undertaken by the FDTD PiC method with a fully parameterised model of the SWS. Extensive optimisation allowed a prediction of the required output power, Figure 5, of 100W being achievable in the midband with a beam current of 100mA at 14.45kV.

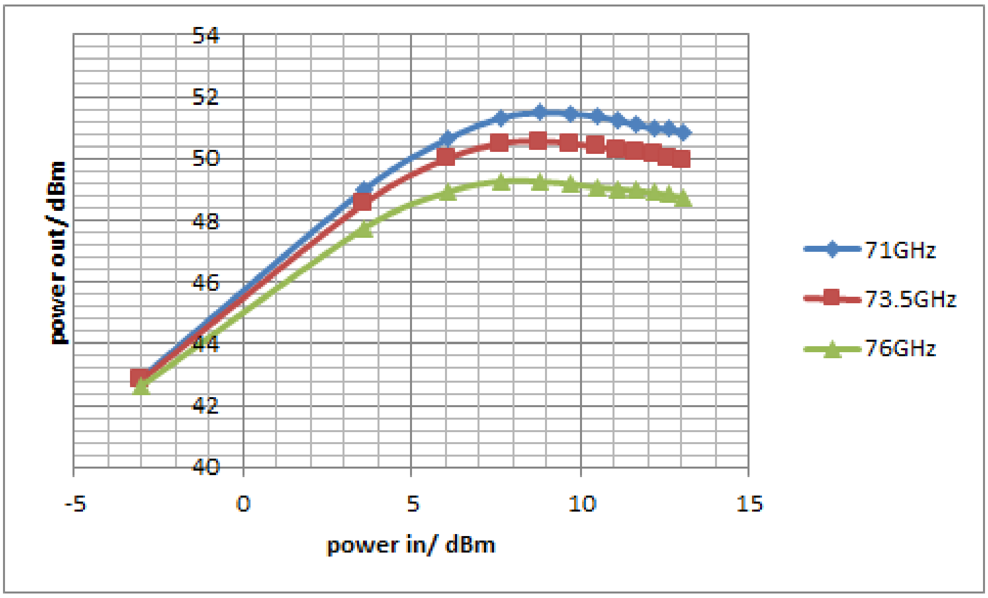

Figure 5 RMS RF power out as a function of RF power in, illustrating the amplifiers transition to saturation at a frequency of 73.5 GHz

The non linear simulations allowed an assessment of the viable efficiency with a multistage depressed collector. It was estimated that at the lower part of the spectral range the efficiency with a 5 stage depressed collector would be lifted from around 10% electronic to about 45% as a device.

4 Electron gun and focussing system

The design of the electron gun and focussing system was undertaken by TMD. The design for the gun was first completed in CST and tested and evolved in Vectorfields simulation software. The design specifications used were: Beam radius: 0.1mm, Beam Current: 100mA, Cathode voltage: -14.55kV, Cathode current density: 3A/cm^2. The Vectorfields simulations were used to optimise the magnet selection for the beam entrance and exit to the slow wave structure. The fields predicted by the simulations are shown in Figure 6. The electron gun used a cathode/heater package made by 3M to a design similar to those used in standard TMD production parts to mitigate risk. Similar the HT insulators were to be taken from standard TMD parts to mitigate lead time and risk.

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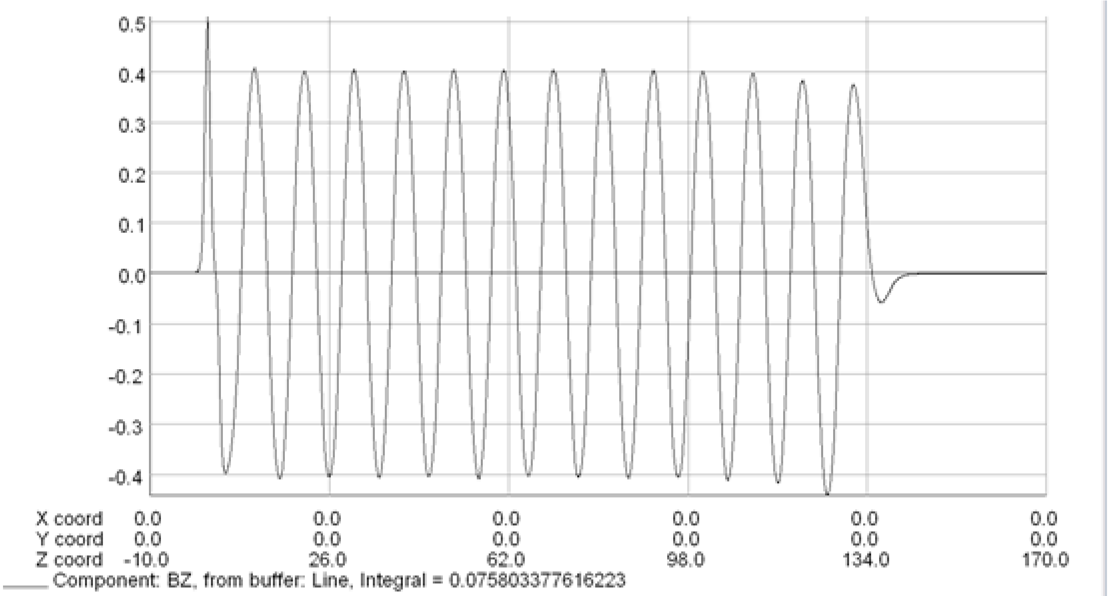

Figure 6: Full magnetic stack in Vectorfields, Opera.

5 Window design

The microwave window is a custom design since the collaboration became concerned about how thin a normal pillbox window would have to be to achieve the required performance at this frequency. The material was chosen to be AlO (DERANOX 970) but the design for the window was derived from a design for much higher frequency in the literature which intended to use BeO ceramic. The design was optimised in simulation for the required frequency range and material. As little data was available at these frequencies for the AlO ceramic, samples of material were subject to measurement to ensure the simulations were using a realistic estimate of the dielectric constant. Once validated in this way custom ceramics were procured from Morgan and a test window structure was designed. The window performance was validated both before and after being brazed into the cavity, see Figure 7. Reasonable agreement was obtained. Extensive investigation looked for ghost modes and the impact of assembly errors in the simulations. Further analysis used the estimated loss tangent to compute the thermal dissipation in the window and resultant deformation of the window and the enclosure. These were not a cause for concern.

6 Collector design

The collector was designed using analytical methods (free beam expansion) and beam trajectory modelling, with simulations predicting the heat loading on different parts of the collector structure. Analytical fluid flow calculations were used to compute a thermal solution for the cooling jacket. It was decided to implement a single stage depression scheme simply to reduce thermal stress on the breadboard. This used a 100kΩ resistor with tap offs at 10kΩ spacing to allow the degree of depression to be controlled. The resistor and its installation were tested and shown to be capable of handling the full power continuously at maximum anticipated depression of 10kV. As the fluid mechanical design argument for the cooling solution had been complex, the arrangement was tested with a full power load onto a representative collector geometry. The water cooling system had no difficulty in removing the maximum anticipated power load with no perceptible increase in coolant temperature.

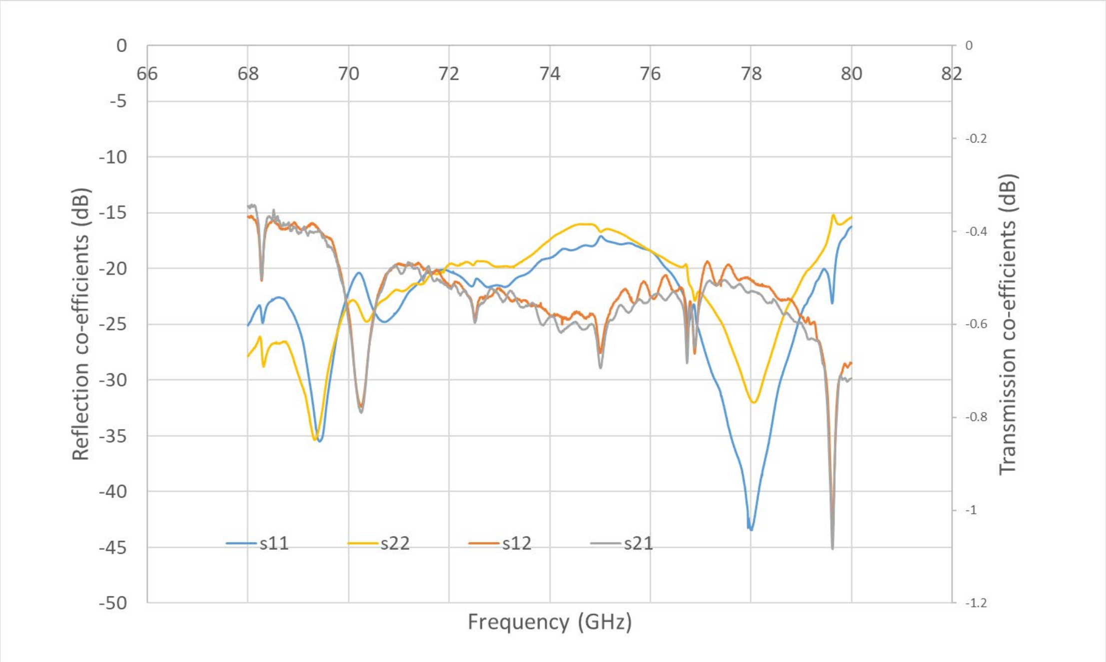

Figure 7: Measurement of the brazed window in the production window cavity.

7 Analysis of potential limiting factors

Multipaction and thermal heating of the delay line were considered as potential physical limiting parameters. Thermal heating of the delay line due to the RF signal at maximum power was found to be negligible. The impact of about 10% of beam current on the output end of the structure was considered and found to produce a modest temperature increase, making reasonable assumptions about the environment and the thermal path linking the core of the delay line to the environment – one of the key advantages of the folder waveguide approach is the better cooling provided by a monolithic structure. This was not expected to significantly impact the dispersion of the delay line. Multipaction was considered by analysis, where only very high order multipaction was indicated as a potential issue. Numerical simulation only saw RF field emission multipaction under some extreme choices for the field emission process.

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8 Build process

The Breadboards were to be built by precision milling in sections of IO waveguide and delay line, each element being machined in two halves in Glidcop (AL15), diffusion bonding the halves together and brazing the components together. There were of course two IO waveguide components, but for this experimental device it was decided to bring the sever ports out through windows- to avoid diffusion bonding on BeO loads and to allow additional diagnostic measurement. The process was derisked in phases – the diffusion bonding test components revealed issues with the flatness of the bonding surfaces necessitating diamond tip cutting of these to better than 50nm surface finish. This was resolved in the 'joining test component' however this revealed that swelling during diffusion bonding forbade a transition fit for the IO components into the delay line sections. It also showed the vulnerability of the Glidcop material to some braze compounds that might have been needed during assemble. Subsequent parts used Ni plating to protect the Glidcop from the braze processes. For the 1st breadboard the interfaces were redesigned and 30µm clearance between the bosses and sockets of the alignment interfaces was found adequate to allow assembly after diffusion bonding and was sufficient for good microwave performance. However the 1st breadboard did not braze on the very small lands possible with this assembly technique. It was thought that the delay line may have 'jacked' under heating in the braze furnace resulting in large gaps. Under a CCN and additional funding from ESA the project attempted to redesign the interfaces to a scheme that would enhance the chances of getting a sealed unit. The components made for this are shown in Figure 8.

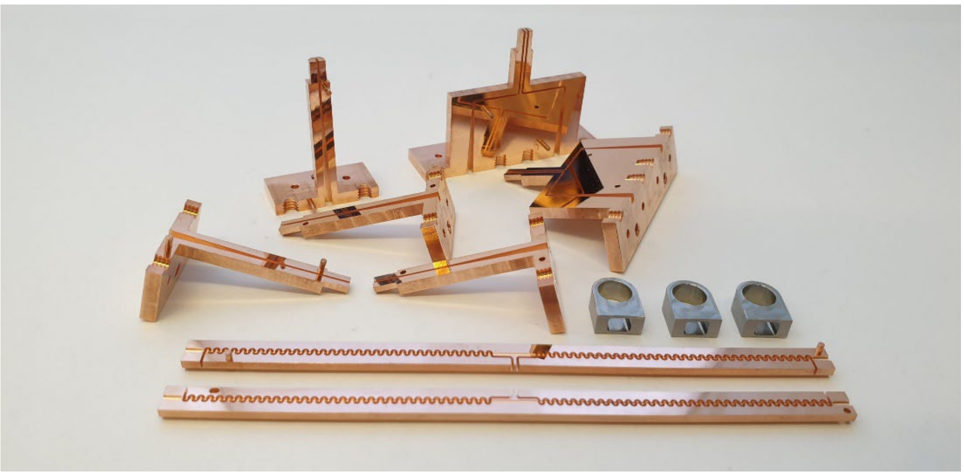

Figure 8 Individual parts of the 2nd breadboard re-design just after fabrication at RAL-space

Unfortunately this component also did not yield a sealed BB TWT. It did however give well seated delay line to IO structure interfaces. The assembled structure produced with these components is shown in Figure 9.

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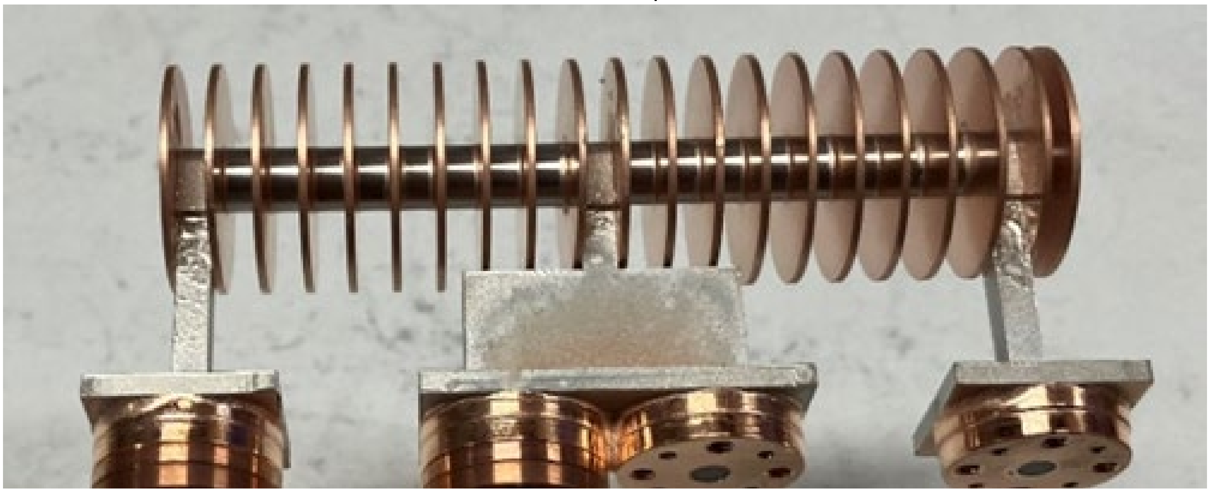

Figure 9 2nd breadboard with windows attached – air side irises mounted on the left hand side ports – absent on the RHS ports. Gun side has the short pole-piece spacer RHS.

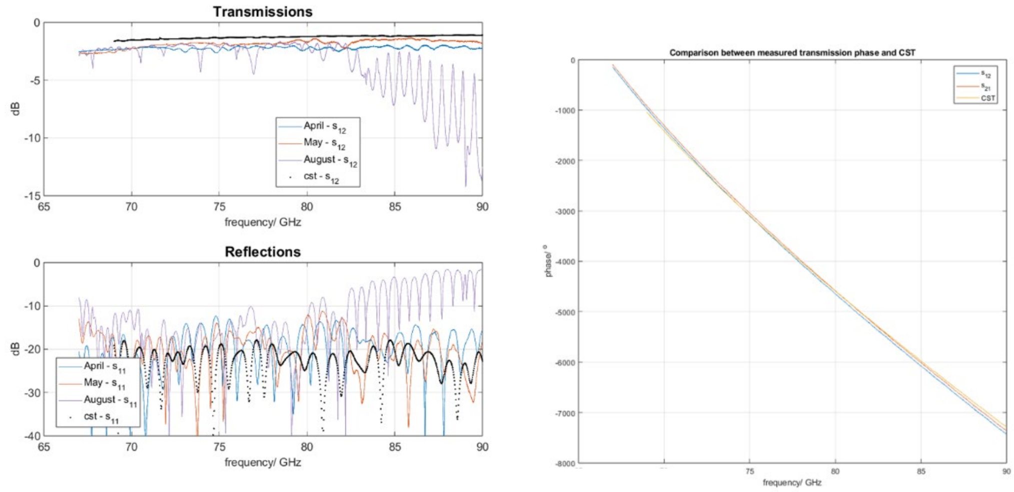

Figure 10: a) Comparison of multiple measurements of the output section for the breadboard TWT. Note the results have been broadly consistent over all measurements in the operating band for the amplifier. Upper plot shows transmission, lower plot reflection, b) Comparison of the measured transmitted phase evolution and the phase evolution from CST simulations

9 Microwave performance

Prior to attaching the windows, a marked difference was noted in the performance of the upstream and downstream elements of the delay line. The reason for this is believed to be a reflection from just beyond the bend in the delay line section sever port on the upstream side. The cause of this is unknown at present. The downstream side gave very good agreement in magnitude with the

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expectation of simulation and both sides gave good agreement in terms of the phase evolution for the transmission measurements. These are shown in Figure 10.The Measurements, taken in April, had the pole-piece spacers which provide the location for the IO waveguides brazed into position, but gravity alone was securing this to the IO components. The measurements in May were taken with the entire assembly brazed together but without windows. The measurements in August were obtained with the windows in place.

There is a slight deterioration in performance with the addition of the windows, specifically certain resonances emerged. These are thought to be alignment issues with one of the windows in the downstream end. Note that no change was seen in the performance of the upstream end, though that had sufficient resonances internally that it might have been difficult to see any effects introduced by the windows.

10 Beam Tests

A beamstick has been created by brazing the electron gun to the collector. At the present time the beam is not being transported to the collector. As the cathode beds in there is evidence of the beam focussing more effectively.

11 Forward planning

A four phase forward plan has been proposed. Phase 1 will develop the deign to enhance performance, particularly efficiency, optimised to run backed off from saturation whilst in parallel derisking the processes that were identified as problematic for the present project. Phase 2 would attempt to complete the BB TWT planned for this activity whilst phase 3 would develop an Engineering Model – full performance but not space qualified. Phase 4 would be a flight candidate where all processes have been space qualified. It is proposed the engineering model and flight candidate should be subject to a test regime exceeding likely thermal and vibration stresses by at least 25% to establish the robustness of the design. It is estimated that €1.5M and 3 years would be required to reach phase 3 building on the position we have established in the present project.

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