TESTING OF THE QWR SERIES FOR THE NEW ISIS MEBT

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Abstract

The quarter wave resonator (QWR, a.k.a. λ/4 resonator) for the new ISIS MEBT is a bunching cavity that longitudinally compresses the H^- beam into smaller bunches. It has two gaps with a distance of $\beta\lambda/2$ between mid-gaps, and works in π mode at the resonant frequency of 202.5 MHz, with a phase angle of -90 degrees, and a maximum voltage per gap (E_0L) of 55 kV. The detailed RF and thermal design were developed, followed by the manufacturing and testing of a prototype, all presented elsewhere. Parts for 5 new cavities were later manufactured, whose details were also presented elsewhere. This paper discusses how these new cavities were assembled, tuned and tested. The assembly was done in the metrology lab to ensure the correct alignment of the nose cones to the stem ring, with the subsequent doweling. Unexpected problems were also found, including the installation of the automatic tuner finger-strips, how to achieve the expected quality factor and the conditioning of the cavities to cope with multipacting.

MANUFACTURING, ASSEMBLY AND TUNING

The current ISIS LINAC directly connects the RFQ to the first DTL tank at an energy of 665 keV. A MEBT was designed to improve the beam matching and to add other beam chopping features. The new MEBT consists of four QWRs, a beam chopper and eight quadrupole magnets.

The electromagnetic, thermal and mechanical designs, including the manufacturing, of a first prototype for the new QWR cavity were previously presented [1, 2]. A first prototype was assembled, tuned and successfully tested [3], which led to the manufacturing of the remaining parts for the series production of 5 additional cavities.

All production tanks for the cavities followed the same manufacturing method as in the prototype cavity, which involved machining from a solid billet to minimise welding.

The brazing jig was optimised to improve the disassembly process. Key changes included reducing the contact area for sliding parts and modifying the tapered section to have 3 points of contact rather than a full ring. Pushing screws were added for all parts to aid disassembly.

New stems and lids were ordered after the success of the prototype. The manufacturer proposed to use C110 rather than the specified C103 copper. The grade is a purer grade with better electrical properties, so the material change was agreed after discussing with the brazing company. When brazing the first of the production cavities, the brazing result did not follow the prototype result of the C103 lids and stems, which was identified as a wetting problem with the purer C110 copper when brazed in vacuum. At this point, it was decided to manufacture new C103 lids but continue to use the C110 stems due to cost and complexity of that part. Further to this, it was found that the diameter of the lip at the top of the stainless-steel tanks, which is a location feature for the lid, varied by up to 40 µm between cavities. Each lid needed to be machined to match each cavity.

To check the suitability of C103 lids with C110 stems, several test pieces were brazed which passed visual inspection and leak checks to give confidence. The production brazes were an improvement on the C110 set but did not completely replicate the success of the trial pieces.

In fact, the outcome of different brazes varied significantly between each tank. Examples included excess flow, partial flow and no flow through the joint (Fig. 1), all with the same parameters.

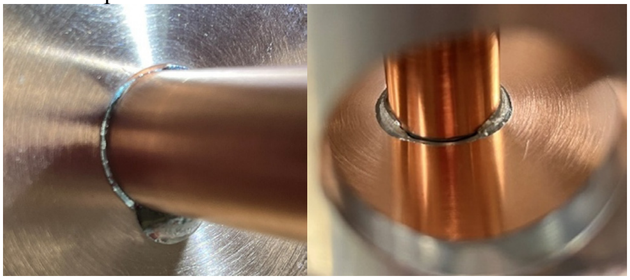
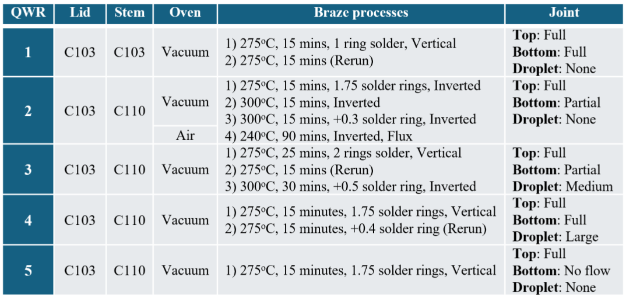


Figure 1: Braze joint problems.

Many of the cavities were brazed multiple times to improve the joint (Fig. 2). Eventually, only 4 out of the 5 cavities passed the vacuum leak test. It was decided to braze the failed one in an air oven rather than a vacuum oven, to allow the use of soldering flux. This was successful, although it needed thorough cleaning to remove the flux and polishing of the tarnished surfaces.



QWR	Lid	Stem	Oven	Braze processes	Joint
1	C103	C103	Vacuum	1) 275°C, 15 mins, 1 ring solder, Vertical 2) 275°C, 15 mins (Rerun)	**Top**: Full **Bottom**: Full **Droplet**: None
2	C103	C110	Vacuum Air	1) 275°C, 15 mins, 1.75 solder rings, Inverted 2) 300°C, 15 mins, Inverted 3) 300°C, 15 mins, +0.3 solder ring, Inverted 4) 240°C, 90 mins, Inverted, Flux	**Top**: Full **Bottom**: Partial **Droplet**: None
3	C103	C110	Vacuum	1) 275°C, 25 mins, 2 rings solder, Vertical 2) 275°C, 15 mins (Rerun) 3) 300°C, 30 mins, +0.5 solder ring, Inverted	**Top**: Full **Bottom**: Partial **Droplet**: Medium
4	C103	C110	Vacuum	1) 275°C, 15 minutes, 1.75 solder rings, Vertical 2) 275°C, 15 minutes, +0.4 solder ring (Rerun)	**Top**: Full **Bottom**: Full **Droplet**: Large
5	C103	C110	Vacuum	1) 275°C, 15 minutes, 1.75 solder rings, Vertical	**Top**: Full **Bottom**: No flow **Droplet**: None

Figure 2: Cavity braze parameters.

The main problem later identified was the reduced silver content of C110 copper and the variability of the outcome due to the low temperature of the braze (275 ºC). The water channel joint, brazed at higher temperature (1000 ºC), produced consistent results each time without any problems.

After brazing, the stem and lids were aligned inside each final tank in metrology, where the cavity and stem offset were measured. They were finally dowelled to allow for repeatable assembly and fix the rotation of the lid.

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The top lid finger-strips were initially installed in the first new tank with a copper shim (as in the prototype), to account for the larger groove size in the already manufactured tanks. However, a poor quality factor was measured in the VNA. It was decided to remove the shim and use the next standard size for finger-strips, to increase the pressure on the lid while avoiding the interface contact between the shim and the copper plated tank (Fig. 3). This change increased the quality factor from 77% to 83% of the theoretical one, still lower than the prototype but within the expectations. The lower quality factor was most likely due to the new tanks' dimensions of the finger-strip groove in the power coupler port, even with a 0.5 mm shim installed.

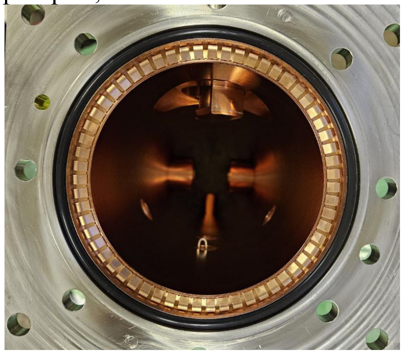


Figure 3: Top lid finger-strips.

Another problem was found when installing the finger-strips for the automatic tuner ports. The grooves in the new manufactured tanks showed a large variability, which required the use (trial and error) of different size copper wires to lock the finger-strips in the groove. The smaller diameter of the hole also required to slightly reduce the diameter of the automatic tuner plugs (-0.3 mm) to reduce friction, which slightly reduced the tuning range of the tuners.

During the tuning of the pickup loops it was found that they were mainly picking on the electric fields (too much signal when rotated 90° against the B field). It was decided to use simpler electric pickups, with just a bit of straight wire (rounded tip) inserted in the feedthrough pin.

Each QWR was measured (in atmospheric pressure) with a range of manual tuner insertion depths by shimming the port flange, with the automatic tuner located at a position that left most of the tuning range in the direction of the cavity heating. The final dimension for each manual tuner plug was interpolated in a spreadsheet, taking into account the temperature and the effect of the air in the measurements, so the final resonant frequency at 20 ºC when in vacuum would be 202.5 MHz.

VACUUM MEASUREMENTS AND WATER FITTINGS

The cavities were tested for vacuum leaks (Fig. 4). Each one was measured with a VNA to check the tuning of the resonant frequency, which showed a successful manual tuner setting in all of them (minor adjustments of the automatic tuner were needed to achieve 202.5 MHz depending on the ambient temperature). The two central pickup ports were individually calibrated for the signal output in resonance (Table 1), to measure the power inside the cavity.

Table 1: QWR Parameters

#	Measured Q_L	RF peak power for nominal V_{gap} [kW]	Pickup 1 loss [dB]	Pickup 2 loss [dB]
1	1916	5.341	-40.35	-37.57
2	1900	5.386	-41.20	-37.95
3	2000	5.116	-41.68	-39.08
4	1980	5.168	-41.25	-38.62
5	2025	5.053	-41.77	-38.47

The water fittings for the cooling system were assembled and pressure tested up to 8 bar for 30 minutes to check for leaks (Fig. 4). The tightening of the fittings was done while the cavities were connected to a VNA to ensure that the resonant frequency was not being too affected.

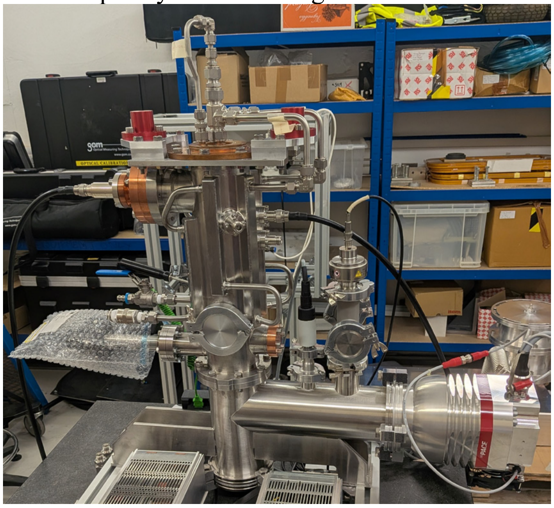


Figure 4: Water assembly and vacuum testing.

HIGH POWER TESTING

The cavities were connected to the 10 kW solid state amplifiers for the initial testing and conditioning. Their initial behaviour was very consistent; all showed a very fast breakdown conditioning (almost no breakdown events at peak power), much better than the prototype, with little to no x-ray external radiation measured by a Geiger counter, and very small vacuum degradation. This was most likely due to the mirror polishing of the critical copper surfaces inside the cavities, something that was not previously done with the prototype.

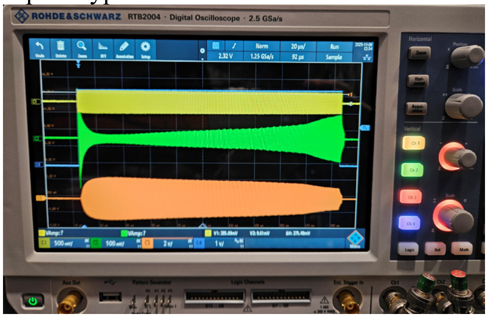


Figure 5: Initial pulses into QWR 1.

The initial pulses after first powering QWR 1 are shown in Fig. 5, where the reflected power (green) increases during the pulse as the RF fields collapse inside the cavity (orange). This behaviour happened for a few minutes before QWR 1 was able to absorb all RF pulses.

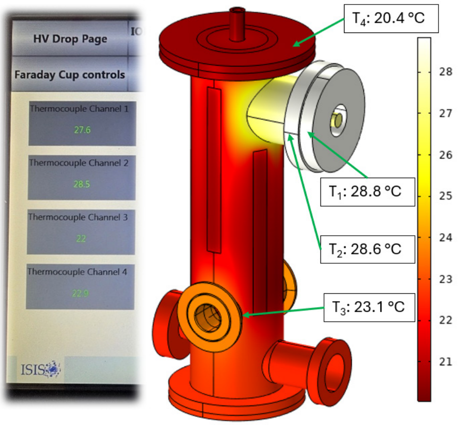
Multipacting

Multipacting was expected in the new cavities, as was seen in the prototype [3], hence a permanent magnet was installed by default in all of them. However, multipacting was much stronger than predicted during the conditioning phase, which was a surprise in the first tested cavity (QWR 1). During the conditioning process, the power in QWR 1 was temporarily increased to 9 kW to discern between breakdown conditioning and multipacting. The Geiger counter was able to record x-ray counts above background while no reflected pulses were observed at that power, which confirmed that the problems at lower power levels were due to multipacting. However, the multipacting was happening below 2 kW, which was a much higher level than in the prototype.

A second magnet was tested on top of the cavity to improve the multipacting behaviour, which worked well, but still not good enough for operation. However, after a few hours powering the cavity and investigating the problem, it was found that the cavity had reduced the multipacting power level from 2 kW to 1 kW. The cavity was left heavily multipacting with a single magnet at 500 W for a few hours and the multipacting limit further reduced to 700 W. This process was confirmed and consistent in the other cavities.

Thermal Tests

All cavities were run initially with thermocouples attached to several critical surfaces. None of them showed anomalous temperatures during the short runs at nominal power (up to 5h). It was decided that only one of them needed to be tested to check that the steady-state FEM predicted temperatures were correct. QWR 3 was left running overnight at 5.2 kW with a safety trip temperature setting of 37 ºC and the nominal water-cooling flow rate.



Thermocouple Channel 1: 27.6
Thermocouple Channel 2: 28.5
Thermocouple Channel 3: 22
Thermocouple Channel 4: 22.9

Figure 6: Temperature at 4 surface points (ºC).

The steady state temperature of the power coupler flange (hot spot in the cavity) was 28.5 ºC after 18 h (Fig. 6), totally in agreement with the FEM thermal models [1].

Gap Voltage Measurements

One of the new cavities (QWR 3) was also measured with an x-ray spectrometer to indirectly work out the gap voltage vs. input power from the x-ray emission spectrum. The idea was to measure the spectrum at 3 power levels around the nominal one (5 kW), but it was soon observed that the count rate of the spectrometer was extremely slow compared to the prototype QWR, which was not enough to get sensible data given the limited time to do the measurements. This had to do with the much better conditioning and surface finish in these new cavities, which produced a very low dose rate of x-rays (and most were anyway shielded by the cavity body).

Several spectra were still recorded at much higher powers than nominal, trying to increase the x-ray emission to get a sensible data point for comparison with FEM results. Those spectra were taken at about 7.24 kW (Fig. 7) and 7.94 kW, while limited to about 1h recording time, and looked similar in shape to the ones presented in [3].

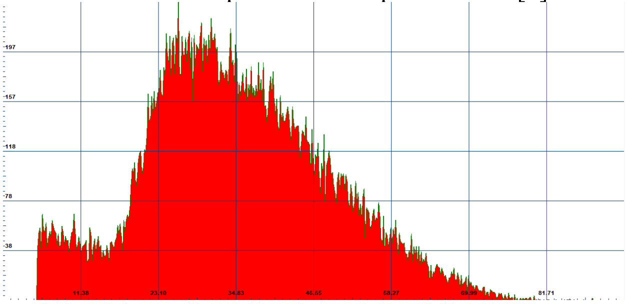


Figure 7: X-ray spectrum at 7.24 kW.

The maximum x-ray energy values were not sharply defined in the spectra due to the lack of an automatic loop control in the tuner, the lack of a low-level RF closed loop in the amplifier control and the short measurement time, but they could be roughly estimated to 81.5 kV and 86.6 kV respectively.

The measured quality factor vs. the theoretical one was used to calculate the actual shunt impedance for the real cavity, which was then used to calculate the voltage in the gaps. By using the ratio of peak voltage vs. gap voltage from FEM simulations, the peak electron voltages were calculated as 81 kV and 84.9 kV at the measurement power levels respectively, not too far from the spectra values.

CONCLUSION

The presented manufacturing and testing of the series QWR cavities for the ISIS MEBT confirmed a successful design and development work during the previous years.

Some unexpected manufacturing problems were solved (brazed joints and finger-strip contacts), while all cavities showed a good conditioning behaviour. The additional multipacting problem was controlled by conditioning the RF surfaces under their own electron bombardment. The thermal tests also showed a robust cooling design. The x-ray results gave confidence that the new cavities were behaving as expected, while their final power settings should be fine-tuned using the beamline diagnostics during the commissioning phase.

REFERENCES

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