FIRST RESULTS FROM THE ISIS RFQ TEST STAND

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Abstract

The ISIS RFQ is a 665 keV, 202.5 MHz 4-rod RFQ designed in collaboration between RAL and Frankfurt University. It is intended to replace the Cockcroft-Walton pre-injector currently in use on the ISIS spallation neutron source at the Rutherford Appleton Laboratory. A test stand has been constructed to allow for an extended period of offline test and measurement before final installation. This paper presents the results of those experiments completed on the test stand so far.

1 THE ISIS RFQ TEST STAND

The Rutherford Appleton Laboratory (RAL) is home to the world's leading spallation neutron source ISIS [1]. The tantalum spallation target is driven by an 800 MeV, 200 μA proton beam from a rapid cycling 50 Hz synchrotron fed by a 70 MeV H^- drift tube linac which in turn is preceded by a 665 keV Cockcroft-Walton preinjector. Due in part to the 1950s vintage of the Cockcroft-Walton pre-injector it is planned to replace the DC accelerating column with a radio frequency quadrupole (RFQ) accelerator [2][3]. As well as the benefits gained through replacing this old and sometimes unreliable equipment, significant improvements in beam transmission from ion source to linac are expected. The extra beam current thus delivered to the synchrotron will be important for the planned 300 μA ISIS upgrade.

In order to fully test and characterise the RFQ without compromising the excellent operational reliability of ISIS, an RFQ test stand has been constructed at RAL and is fully described in [4]. The test stand provides a radiation-shielded environment containing all the services and diagnostics necessary to run and monitor the RFQ. Before installation on ISIS the RFQ will be run on the test stand 24 hours a day for the equivalent of several ISIS user runs.

2 LOW POWER MEASUREMENTS

2.1 Delivery and Alignment

The RFQ was delivered to RAL on 11th September 1999 and was mounted and aligned on the test stand. The tuner was delivered in October and was fitted following repair necessitated by in-transit damage. From September to December 1999 the RFQ underwent extensive vacuum leak testing and the many water connections from the dedicated chillers were made to the RFQ vessel cooling circuits.

2.2 Initial Q Measurement

Very low power RF measurements began on 22nd October 1999 with the RFQ still at atmosphere, *i.e.* not under vacuum. Using a signal generator and network analyser the unloaded Q of the RFQ was measured at

$$Q_0 = 2600 \pm 200$$

by observing the 3dB bandwidth. This is rather low compared to the MAFIA [5] calculated value of 7500, even allowing for the overestimation of Q commonly achieved by use of MAFIA.

2.3 Low Power Measurements

The RFQ was pumped down using only one of the two turbo-molecular pumps (TMPs) fitted to the vessel and a pressure of 3×10^{-7} mbar was achieved. On 28th October ~1 kW peak RF power with a duty cycle of 2% was delivered to the RFQ. It was observed that after several minutes of running, the RF match into the RFQ suddenly improved and the signal strength from the field pick-ups increased. The initial belief was that this was due to dirt on the electrode surfaces that would condition away although the effect is still observed after nearly 100 hours of high power operation.

The Q was measured at the 1 kW RF level by observing the 3dB bandwidth at the field pick-ups and was in agreement with the initial measurement although there was some spread in the values due to the differing and asymmetric signals from the four loops. The Q was also determined from the transient response of the RFQ leading to a value of

$$Q_0 = 2700 \pm 200$$

which is in good agreement with the value determined from the bandwidth at very low power.

Based on this value of unloaded Q the calculated power required to reach the design inter-electrode voltage of 90 kV is 230 kW peak (23 kW mean for a duty cycle of 10%) which is a little higher than initially anticipated.

3 HIGH POWER CONDITIONING

On 18th November 1999 water was pumped at the full flow rate of 3 litre/min through all the cooling channels with the vessel under vacuum. With water circulating and no RF power the vacuum pressure was $1.9\text{x}10^{-7}$ mbar with one TMP running. Following safety approval on 29th November high power RF was delivered to the RFQ for the first time on 2nd December.

The RF power and duty cycle were slowly increased and after a period of 33 hours conditioning a level of 160 kW with a pulse length of 500 µs at 50 Hz pulse repetition frequency was achieved (2.5% duty cycle). The vacuum pressure at this level was 1.6×10^{-6} mbar. Increasing the power beyond this level (peak power or duty cycle) resulted in excessive sparking and increases in vacuum pressure, which proved difficult to condition away. Power levels of 200 kW were achieved but could not be maintained for any period of time. By 21st December no further progress had been made in achieving higher powers in the RFQ when the system was shut down for the Christmas vacation. Upon re-powering the RFQ, a level of 160 kW at a duty cycle of 2.5% was again quickly established but no further increases were possible due to sparking. Despite a further >50 hours conditioning, 160 kW remains the highest power that can be achieved without sparking at this duty cycle.

Figure 1 shows the RFQ vacuum pressure as a function of peak RF power.

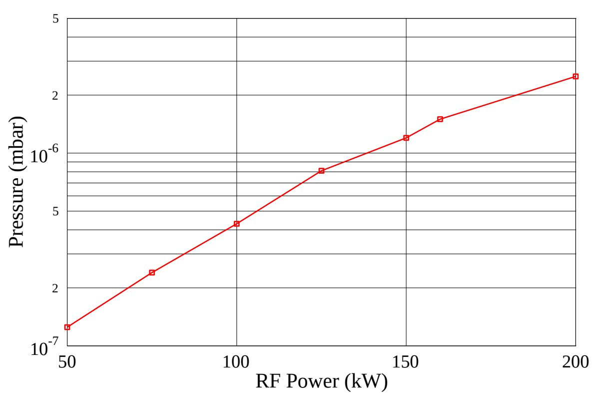

Figure 1: Vacuum pressure in the ISIS RFQ for different peak RF powers (50 Hz, 2.5% duty cycle) with one TMP running.

It is hoped that a further extended period of conditioning at high power will eventually lead to operation at powers sufficient to achieve the design voltage on the electrodes.

4 RF LOSSES IN ELECTRODES

In order to determine if the difficulty encountered in conditioning the RFQ was due to overheating of the electrodes, an attempt was made to estimate the RF losses on the electrode surfaces.

Each of the four rod electrodes has its own independent water cooling circuit. By reducing the flow rate and measuring the difference between the coolant output and input temperatures an estimate of the power dissipation can be made. The measured water temperature increases for a flow rate of 0.6 litre/min are given in Table 1. Figure 2 shows the associated RF losses.

Table 1: Temperature increases in electrode 1 coolant.

Mean RF Power (W)	**Electrode Water Temp. Rise (°C)**	**Electrode Power Dissipation (W)**
740	0.9	37.8
1130	1.4	58.8
1545	2.1	88.2
1860	2.6	109.2
2230	3.4	142.8

At ~5–6% of the total losses, these figures agree well with simulation and suggest that no overheating of the electrodes is occurring. To double-check, a barium fluoride (BaF_2) window has been fitted to a diagnostic port on the RFQ. This material is transparent to infrared at the appropriate wavelengths so the electrode temperature can be monitored directly via its infrared during the next period of high power operation.

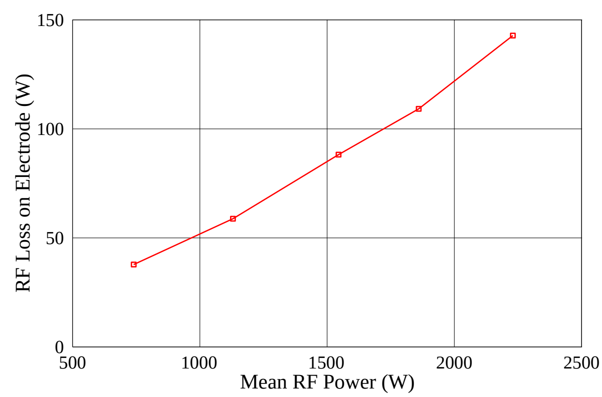

Figure 2: RF losses in electrode 1.

5 INTER-ELECTRODE VOLTAGE MEASUREMENT

A system consisting of an HPGe gamma-ray spectrometer with an ultra-thin entrance window and multi-channel analyser has been installed to determine the inter-electrode voltage in the RFQ by measuring the endpoint of X-rays emitted when RF power is applied.

The RFQ is contained within a 5mm thick lead shield to reduce the ~1 mSv/hour dose rates ~0.5 m from the RFQ vessel to <1 µSv/hour outside the shield. A 1.6 mm diameter hole was drilled in the lead to enable X-rays to reach the detector.

A series of spectra and corresponding backgrounds were measured at a range of power levels. The backgrounds were taken with RF running at the same level but with the hole in the shielding covered by 5mm of lead. The energy scale was established using the 26.3 and 59.6 keV lines from a ^{241}Am source. Software has been written to calculate the theoretical thick target bremsstrahlung spectrum of the copper electrodes as a function of inter-electrode voltage. The following effects are integrated into the calculation of the spectrum seen at the detector:

- Sinusoidal time variation of the voltage.
- Field unflatness in the RFQ.
- Four discrete inter-electrode voltages.
- Energy dependent attenuation in the steel RFQ vessel.
- Resolution function of the detector.

A two-dimensional χ^2 fit on mean inter-electrode voltage and a normalisation parameter is performed to find the best fit to the measured data. Table 2 summarises the results of measurements at a range of power levels. Plotting the mean inter-electrode voltage as a function of $\sqrt{}$(power) as in Figure 3 results in a very nearly linear relationship. Figure 4 shows an example of a measured and fitted spectrum.

Table 2: Summary of results from x-ray endpoint measurement of RFQ inter-electrode voltage.

Peak RF Power (kW)	Mean Voltage (kV)	χ^2 of fit
68	55.4 ± 2.4	0.43
93	60.6 ± 0.5	2.8
111	64.7 ± 0.3	3.35
134	69.1 ± 0.2	6.49

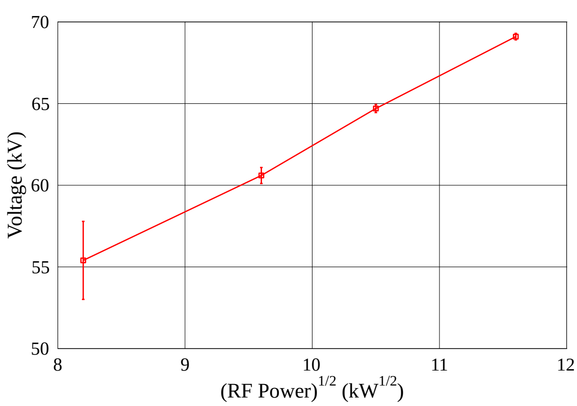

Figure 3: Mean inter-electrode voltage determined by the X-ray endpoint method.

At low mean inter-electrode voltages the quality of the data is relatively poor, largely because the multi-channel analyser was not gated around the RF pulse because of software incompatibilities prevailing at the time. However, in future the multi-channel analyser will be gated to reduce background and the quality of the data is expected to improve significantly.

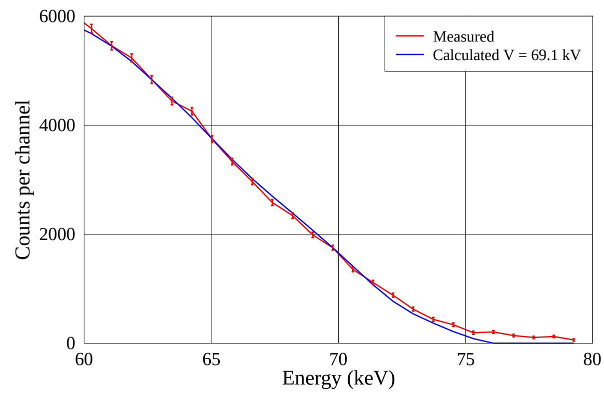

Figure 4: Measured and calculated x-ray spectrum from the RFQ operating with 134 kW peak RF power.

Extrapolating the figures from Table 2 up to the planned operating level leads to a calculated peak RF power of 220 kW for 90 kV mean inter-electrode voltage. This agrees very well with the figure of 230 kW calculated from the Q measured at low power.

The absolute minimum operating voltage suggested by beam dynamics simulations is ~80 kV with a reduction in beam transmission. Based on the figures above the power required to reach this level is ~175 kW. This is close to the reliably achieved peak power for a 2% duty cycle.

REFERENCES

[1] ISIS 99, The ISIS Facility Annual Report, RAL-TR-1999-050 (http://www.isis.rl.ac.uk/isis99/)
[2] H. Vormann et al., “A New High Duty Factor RFQ Injector for ISIS”, EPAC 98, page 782
[3] A. Letchford, A. Schempp, “A Comparison of 4-Rod and 4-Vane RFQ Fields”, EPAC 98, page 1204
[4] D.J.S. Findlay et al., “The Rutherford RFQ Test Stand”, THP4A03, these proceeding
[5] MAFIA electromagnetic field simulation software, CST, Gesellschaft für Computer-Simulationstechnik m.b.H., Darmstadt, Germany (http://www.cst.de/)