1.3 GHz CAVITY TEST PROGRAM FOR ARIEL

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Abstract

The ARIEL eLINAC is a 50 MeV 10 mA electron LINAC [1]. Once finished, five cavities will each provide 10MV of effective accelerating voltage. At the present time two cavities have been installed and successfully accelerated been above specifications of 10 MV/m at a Q0 of 1010. The next cavities are already in the pipeline and being processed. In addition, one additional cavity has been produced for our collaboration with VECC, India. This cavity has been tested and installed in a cryomodule identical to the eLINAC injector cryomodule.

New developments for single cell testing at TRIUMF are a T-mapping system developed in collaboration with UoT and vertical EP for single cells in collaboration with KEK.
The progress of the performance after each treatment step has been measured and will be shown.

INTRODUCTION

ARIEL will complement the existing accelerator complex at TRIUMF with its rare isotope program. With the addition of the eLINAC up to three out of ten experimental stations (currently one out of ten) can receive rare isotope beams (RIBs). The production of the RIBs is done via photo fission that utilizes the 50 MeV 10 mA continuous wave (cw) e- beam from the eLINAC. In the finished eLINAC three cryomodules house five 1.3 GHz nine-cell cavities. The design gradient for each cavity is 10 MV/m. The cryomodules are split into one injector cryomodule (ICM) with one cavity and two accelerator cryomodules (ACM) with two cavities each. At the time of writing the injector cryomodule is completed and accelerated a low intensity beam successfully to about 12 MeV, surpassing the design gradient. The first ACM was initially installed with only one cavity due to time constrains. As soon as the second cavity is ready, the cryomodule will be removed from the beam line and outfitted with the second cavity.

Since the last time reported, two nine-cell cavities have been fully tested and installed into cryomodules. One additional cavity has passed the vertical testing phase and its helium jacket is being dressed with its helium jacket. A fourth cavity is in the vertical testing phase and showed a good performance.

VERTICAL CAVITY TESTS

All vertical tests use a similar self excited loop to control the RF frequency and amplitude as the ISAC-II system. A frequency mixer down- and upconverts the 1.3 GHz signal to the ISAC-II high-β cavity frequency of 140 MHz, so that the the signal is in a useful range. The cryostat is equipped with several temperature sensors spread out over the cavity, LHe level probes, heaters, and pressure sensors for operation at 2 K. A variable coupler is attached to the nine-cell cavity, providing a coupling range from 10^7 to 10^{11} [2]. This allows for critical coupling at 4.2 K (expected $Q_0 \sim 4 \cdot 10^8$) and 2 K ($Q_0 \sim 1 \cdot 10^{10}$) and at the same time a useful overcoupling for pulsed conditioning if needed. The cryogenic system is limited to about 20 W of active load at 2 K before the He vapor pressure regulation system cannot compensate. A background magnetic field of about 1 μT inside the cryostat was measured, leaving only a small contribution to the surface resistance in the measured cavities.

ARIEL1

In [2] the first vertical tests of the first nine-cell cavity, ARIEL1, were shown. The cavity showed a Q_0 of $5 \cdot 10^9$ at low gradient with moderate slope to $3 \cdot 10^9$ at 10 MV/m. After degassing (800° C, 10 hours, no additional chemistry) at FNAL the Q_0 increased to $6.5 \cdot 10^9$ all the way up to 11 MV/m (see fig. 1). While the Q_0 does not fully meet the goal of $\geq 1 \cdot 10^{10}$, it is sufficient for operation in the ICM.

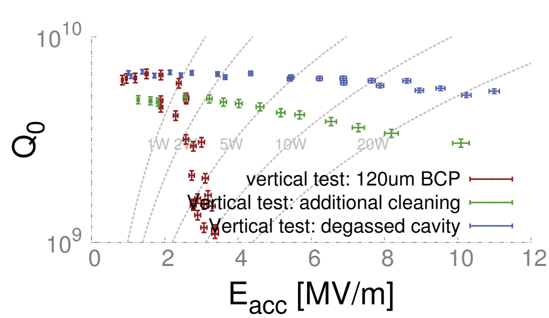

Figure 1: ARIEL1 vertical performance test showed improvements in Q_0 after 800° C degassing.

ARIEL2

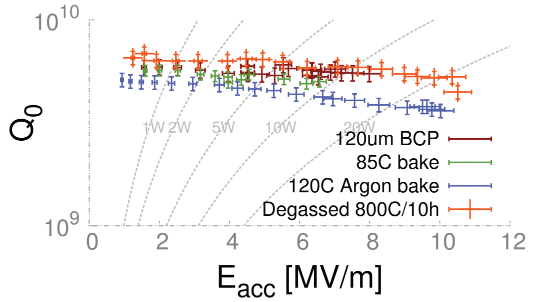

Figure 2: ARIEL2 vertical performance test showed improvements in Q_0 after 800° C degassing.

The second cavity, ARIEL2 (performance test results are shown in fig. 2), was tuned and tested after the initial 120 μm removal via buffered chemical polishing (BCP). The gradient was limited to 8 MV/m due to field emissions with a $Q0$ of $7 \cdot 10^9$. Pulsed conditioning of the cavity did not succeed in reducing the field emissions. In-situ baking inside the cryostat without opening the cavity proved to be insufficient to reach the typical 120° C due to a lack of heater power. After this bake a small decrease in Q_0 could be observed at higher gradients, but falls within the uncertainties of the previous measurement.

A dedicated bake-out station using hot argon gas allowed the temperature to reach 120° C and was held there for 48 h. The following performance test showed a lowered Q_0 compared to the previous test with a gradient up to 10 MV/m, limited by the available cooling power. The decreased Q_0 is caused by a increased residual resistance, which increased from (31.3 ± 0.7) nΩ to (44 ± 2) nΩ. The estimated BCS resistance is unchanged within the measured uncertainties [(14 ± 5) nΩ to (6 ± 4) nΩ].

After the same degassing step at FNAL that ARIEL1 took, the Q_0 recovered to the values from before the 120° C bake up to 10 MV/m. The performance after the following baking and HF rinse steps could not be measured in the vertical test cryostat due to repeated vacuum leaks when the liquid helium enters its super-fluid state at 2.17 K. It is strongly suspected that the knife edges on the coupler ports lost their sharpness after the heat treatment and repeated use. In the cryomodule this will be a vacuum to vacuum connection and the the problem of superfluid helium leaking into the cavity is non-existent.

ARIEL3

More tests could be done on ARIEL3 to improve the Q_0 above the specification of $1 \cdot 10^{10}$ or higher. This cavity is meant for the second injector cryomodule, that is build for the collaboration with VECC in Calcutta (India). At the time of writing the vertical test phase is completed and the helium jacket is being welded on.

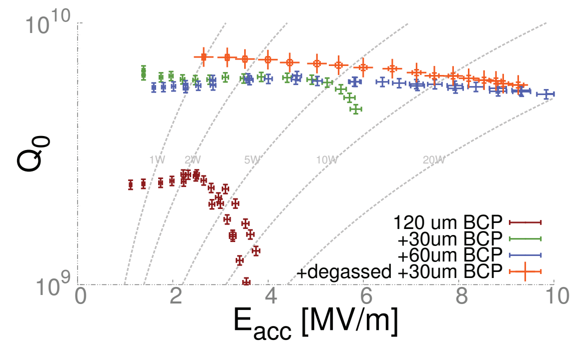

Figure 3: ARIEL3 vertical performance test showed improvements in Q_0 after 800° C degassing.

Multiple removal steps have been performed after the initial performance was very poor with $2 \cdot 10^9$ and strong field emission below 4 MV/m. This indicated a normal conducting inclusion at the surface.

After a 30 μm etch, the performance increased up to $6 \cdot 10^9$ up to 5 MV/m. At higher gradients the Q_0 decreases and x-rays were detectable. It was suspected that the inclusion was not fully removed and further etching is needed to reach higher Q_0 and gradient.

The next test (not shown in fig. 3) showed a very poor performance with a Q_0 of $5 \cdot 10^8$ at 2 K. After inspection of the cavity, scratch marks were found on the irises inside the cavity. Those marks are a result of a misalignment of the cavity in the HPR unit and the wand touched down at the iris. To remove these marks a further 30 μm etch was done and the performance recovered to the previous Q_0 values of $6 \cdot 10^9$ up to 11 MV/m, limited by available cryogenic power.

After this, the cavity was sent for degassing at FNAL to increase the Q_0 and reduce the hydrogen content in the niobium. The experience from the horizontal tests, showed a 30 μm etch pushes the Q_0 to over 10^{10}. During the vertical test a helium leak opened up on the cavity. The helium gas inside the cavity enhances field emissions and a low gradient multi-pacting barrier . In addition the produced x-rays limited the reachable gradient to 9.25 MV/m.

A further 30 μm etch was done to push the Q_0 over 10^{10}. Due to repeated leaks opening up at the super-fluid transition of helium, further 2.0 K tests had been unsuccessful. Testing at 2.3 K, above the super-fluid transition, showed a Q_0 of $3 \cdot 10^9$ with a moderate slope up to 9.5 MV/m. The gradient was limited again by available cryo power. By measuring the Q_0 with different temperatures at a fixed gradient, the BCS resistance and residual resistance were determined to be R_{BCS}(T = 2.0 K)= (11 ± 2) nΩ and R_{res} = (37.2 ± 0.3) nΩ. The BCS resistance at 2.3 K was calculated to be 31 nΩ. By subtracting the difference in R_{BCS} from 2 to 2.3 K from the Q_0 vs E_{acc} data, a baseline Q_0 of $6 \cdot 10^9$ was estimated would the cavity be tested at 2.0 K (fig. 4). This assumes that the difference in BCS

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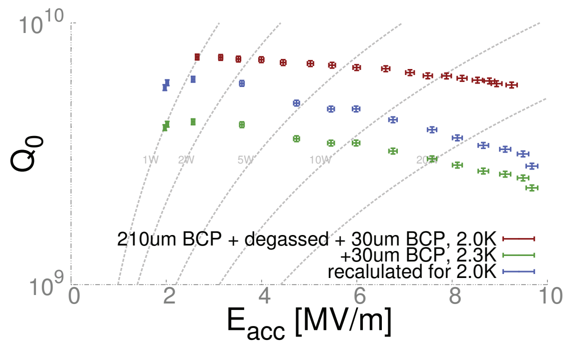

Figure 4: 2.3 K measurements of ARIEL3 showed a decent performance up to 9 MV/m with a moderate slope.

resistance between 2.3 K and 2.0 K stays constant with increasing gradient.

ARIEL4

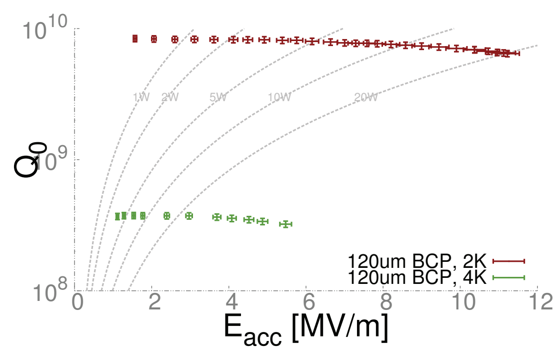

Figure 5: ARIEL4 showed a $Q_)$ of $8 \cdot 10^9$ at 2K up to 11 MV/m.

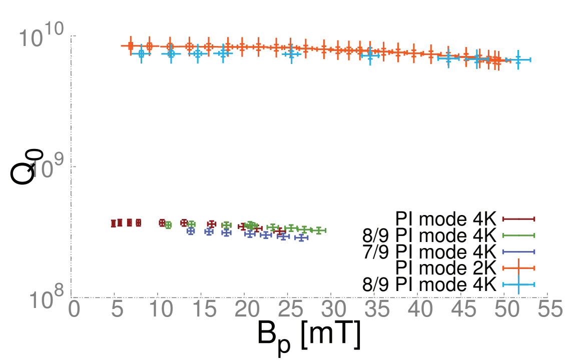

Figure 6: The 7/9 and 8/9π modes showed no difference in Q_0 up to the measured peak surfrace fields.

The fourth multi-cell cavity performed well compared to the previous ARIEL cavities right after the initial 120 μm BCP removal, with a Q_0 of $8 \cdot 10^9$ up to 11 MV/m as shown in fig. 5. In addition to the measurements in the π mode, the performance in the 7/9-π and 8/9-π modes have been measured. No significant differences in Q_0 have been found over the range of measured magnetic peak surface fields B_p as shown in fig. 6. The BCS resistance was fitted to (12 ± 1) nΩ at 2 K and the residual resistance to (22.7 ± 0.2) nΩ. Since the performance was very good compared to the previous cavities at this stage, the cavity was sent directly for degassing to reduce the hydrogen content and increase the Q_0. A 30 μm removal via BCP is planned once the cavity is back at TRIUMF.

CRYOMODULE TESTS

As soon as the cryomodules were installed on the eLINAC beam line, performance measurements commenced. In these horizontal measurements the pick-up voltage to measure the gradient is calibrated by measuring the energy gain of the electron beam. Since the cavities are heavily overcoupled ($\beta \sim 1000$), direct RF power measurements are not possible. Instead the power measurements rely on the helium consumption rate. By closing the helium supply, the dissipated power in the cavity is measured by the rate the liquid helium level in the reservoir on top of the cavity falls.

ICM

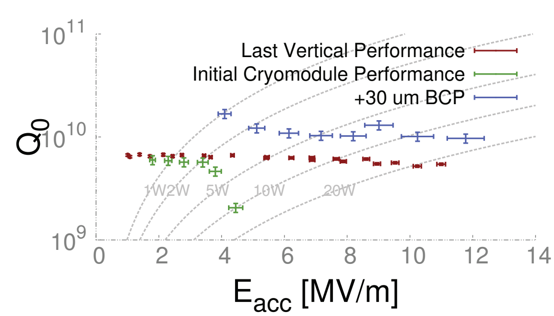

Figure 7: After strong field emissions were found in the cryomodule, a 30 μm etch increased the performance to $1 \cdot 10^{10}$ up to 11 MV/m.

Initially the ICM cavity (ARIEL1) showed a similar Q_0 as in the vertical tests. The gradient was limited to about 5 MV/m (see fig. 7). At this gradient high levels of x-ray radiation were measured, leading to the suspicion that the cavity got contaminated with particulates during the assembly. Pulsed and cw conditioning did not result in any reduction field emission or improvements in gradient/Q_0. By moving the x-ray monitor around the cryomodule the strongest x-rays intensities were measured at the coupler end of the cavity. Since conditioning did not show any improvements, the cryomodule had to be disassembled and the cavity inspected for damage. As it turns out the coaxial HOM beam line absorber touched down on the cavity, damaging the cavity (fig. 8) and creating the field emitters. A 30 μm etch was done to repair the damage on the cavity. After the cavity was sealed and back in the cryomodule, the performance improved to $1 \cdot 10^{10}$ up to a gradient of 11 MV/m. The gradient was limited due to multipacting in the power couplers.

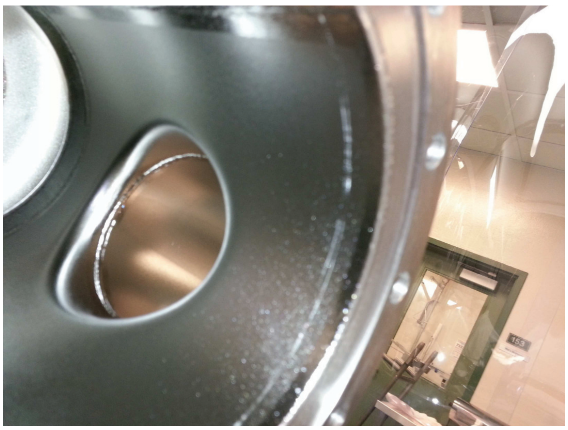

Figure 8: Visible damage on the beam tube cause by the HOM beam line absorbers during assembly.

ACMuno

The last vertical test of the ACMuno cavity (ARIEL2) showed a Q_0 of $5 \cdot 10^9$ up to 11 MV/m. After this test a 120° C bake followed by an HF rinse was done but could not successfully tested in the test cryostat due to super-fluid leaks. The effects of the bake and HF rinse can be seen in the increased performance of this cavity in the cryomodule (see fig. 9). The Q_0 increased to $1 \cdot 10^{10}$ up to 12 MV/m. Again, multipacting in the main couplers prevented reaching higher gradients.

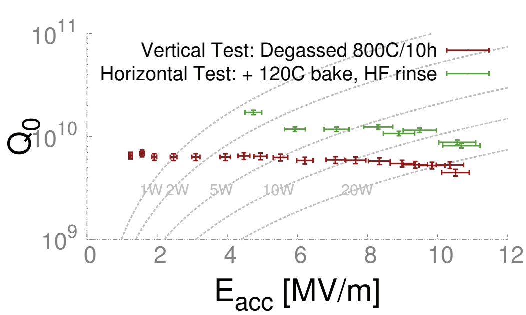

Figure 9: A 120° C bake and HF rinse increased the performance compared to the last vertical test.

T-MAPPING

T-mapping is a common method to identify hot spots on cavities. Usually a series of temperature dependent resistors is pressed against the cavity wall and changes in the resistance are recorded as a function of gradient to localize the hot spots. A system for T-mapping on single cell cavities has been constructed based on the one originally design at Jefferson Lab. It is based on 100 Ohm Allen-Bradley carbon resistors as the temperature sensors. In order to check that the temperature sensors work, we have used a ring of 40 sensors, mounted on the equator of a nine-cell 1.3 GHz cavity (fig. 10). First tests showed promise: clear temperature dependence of the resistance was measured as shown in fig. 11. No increases in temperature during increased RF power in the cavity could be measured because the cavity test was prematurely terminated. However it was confirmed that the sensors were measuring reasonable temperatures around the cell.

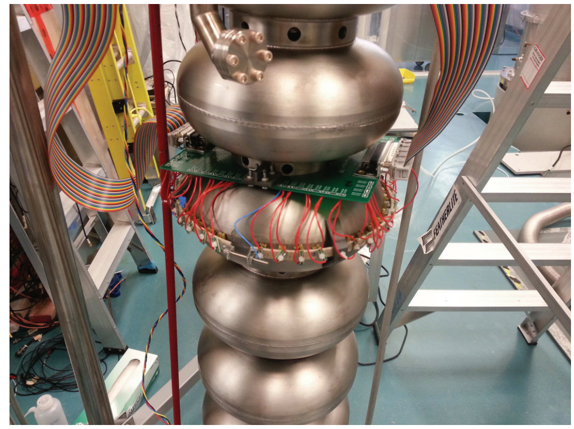

Figure 10: T-mapping test board mounted on a nine-cell cavity ready for testing.

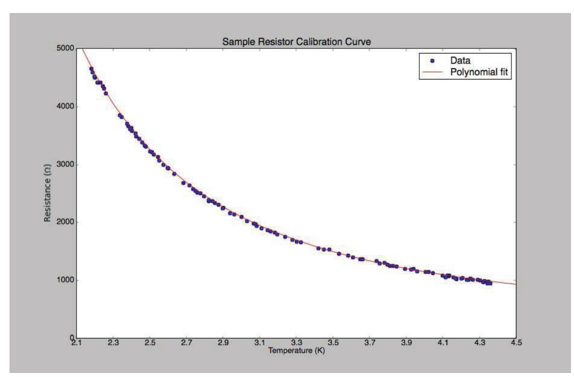

Figure 11: Calibration curve of one of the resistors.

VERTICAL EP

So far only BCP is available at TRIUMF as a surface removal option. Electro-Polishing (EP) is know to produce higher Q_0 than BCP. In an effort to strengthen the R&D capabilities, a vertical EP solution was pursuit. The cathode design (shown in fig. 12) consists of four aluminum paddles that fold and unfold together. The purpose of the paddles is to provide an even etch rate inside the cell compared to the

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iris/beam tube. More details on the TRIUMF system can be found in [3].

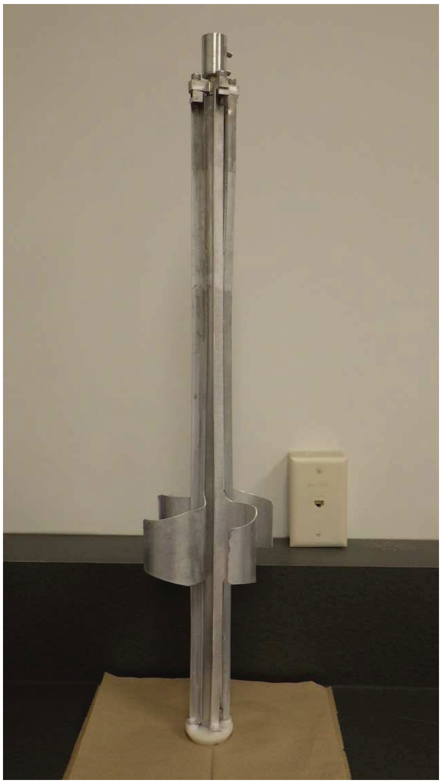

Figure 12: Cathode design of the TRIUMF vertical EP system nick named *D'Sonoqua*.

INDUCTION FURNACE

Figure 13: Assembly of the induction furnace for high T degassing.

Similar to EP, high temperature treatments of cavities are currently unavailable at TRIUMF. An induction furnace for single cell cavities (fig. 13) has been designed and is being build at the time of writing. The design follows the JLAB design [4]. A induction coil heats a Nb susceptor which then transfer heat via radiation into the cavity. Temperatures of up to 1400° C are expected. To verify the functionality of this induction furnace a Nb tube will be used before a full cavity receives any heat treatment.

CONCLUSIONS AND OUTLOOK

In the last years four nine-cell cavities were fabricated and tested. Two of these cavities are now installed in cryomodules. Both cavities successfully accelerated beam to 23 MeV [5] and meet performance specifications with a Q_0 of $1 \cdot 10^{10}$ at 10 MV/m.

One more cavity has finished its vertical testing phase and receives its helium jacket at the time of writing. The fourth cavity showed a good performance after the initial 120 μm BCP and is being degassed at FNAL.

Developments for single cell testing include a T-map system for hot spot detection, vertical EP capabilities and an induction furnace for high temperature treatments. Both the T-map system and the vertical EP concluded in promising first tests.

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