

1.3 GHZ CAVITY DEVELOPMENT AT TRIUMF

R.E. Laxdal, C Beard, P. Kolb, S. Koscielniak, D. Longuevergne, A. Grassellino, V. Zvyagintsev, TRIUMF, Vancouver, Canada, R. Orr, W. Trischuk, U. of Toronto, Toronto, Canada

Abstract

TRIUMF has embarked on a 1.3GHz development program to support the construction of a 50MeV 10mA e-Linac for the production of radioactive ion beams through photo-fission. Two single cell bulk niobium cavities have been produced in Canadian industry. A seven-cell cavity in copper is being fabricated both as a manufacturing model and to test higher order mode calculations. Electromagnetic and mechanical models of a multi-cell cavity are used to optimize the final design for high intensity acceleration. The 1.3GHz cavity development program is presented.

INTRODUCTION

The TRIUMF e-linac[1], now funded, is specified to accelerate 10mA of electrons to 50MeV for a 0.5MW final beam power. The cavities operate at 1.3GHz and 2.0K. The linac consists of three cryomodules; the first, called the injector cryomodule (ICM), holds one multi-cell beta=1 cavity, while the second and third are identical and hold two multi-cell beta=1 cavities each. A schematic of the e-Linac is shown in Fig. 1.

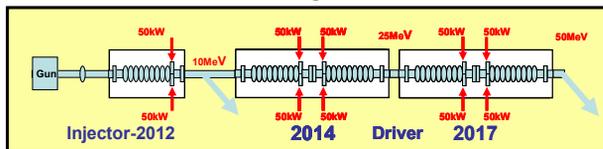


Figure 1: Schematic of e-Linac.

The ICM[2] is being built first but is considered as a prototype for the e-Linac main cryomodules so is being designed with the two cavity cryomodule in mind. The cavities will be housed in a box-like top-loading cryomodule patterned after the modules used for the heavy-ion superconducting ISAC-II linac[3]. A sketch of the accelerating module is shown in Fig. 2.

TRIUMF has been involved in superconducting rf (SRF) cavity development and testing since 2000. An SRF lab was opened in the ISAC-II building in 2004. The lab includes infrastructure for cavity and cryomodule clean assembly and testing and for cavity processing including high pressure water rinse (HPWR) and a buffered chemical polish (BCP) etching laboratory. In 2006 five cryomodules consisting of twenty quarter wave resonators (QWRs) were installed in Phase I of the ISAC-II superconducting heavy ion linac contributing 20MV of accelerating voltage to the ISAC post-acceleration[4]. The cavities were produced in Italy at Zanon and etched in CERN and J-Lab. In 2010 Phase II of the ISAC-II

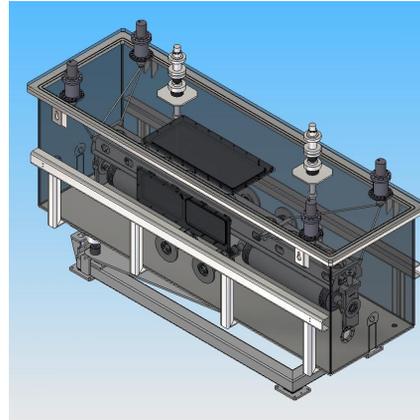


Figure 2: Sketch of the accelerating cryomodule with two multi-cell cavities at 1.3GHz.

installation was completed consisting of the addition of twenty additional QWR's in three modules[5]. These cavities were produced at PAVAC Industries of Richmond BC and chemically etched at TRIUMF.

The cavities for the e-Linac project will be designed at TRIUMF and fabricated at PAVAC with final processing at TRIUMF. A development program to establish the techniques for fabrication and testing of the 1.3GHz cavities was begun in 2008. The aim of the development is to expand the infrastructure to support activities at 1.3GHz and to collaborate with PAVAC on cavity fabrication. This paper summarizes the progress to date.

CAVITY DESCRIPTION

The cavity borrows significantly from the nine cell cavity developed for the Tesla Project and now being used at FLASH and for X-FEL. The Tesla cavity is built for pulsed operation at relatively low intensity and is designed to operate at accelerating gradients in excess of 25MV/m. In comparison the e-Linac cavities will operate in cw mode with very high beam loading but with relatively low gradients. Future upgrades in the e-Linac may involve the addition of a recirculating ring to operate either in energy recovery mode or energy boost mode. The goal of the cavity design study is to slightly modify the Tesla shape in order to handle the higher beam power, the induced higher order modes (HOMs) while keeping well away from beam break-up (BBU) thresholds in multi-pass modes.

Operating Point

The design gradient is determined by the maximum power that can be delivered to the cavity to support the

TRIUMF receives funding via a contribution agreement through the National Research Council of Canada

beam loading. The proven state of the art in power couplers at 1.3GHz is the coupler developed by Cornell and produced by CPI for the Cornell ERL injector[6]. A conservative limit on the operating cw power is 50kW. The power coupler ports will be configured to allow two symmetrically opposed couplers at one end of the cavity to produce a total rf power capability of 100kW/cavity. At 10mA of beam current this corresponds to a maximum effective voltage per cavity of 10MV. This sets the maximum gradient required to $E_a=10\text{MV/m}$ with associated peak surface fields of $E_p=20\text{MV/m}$ and $H_p=43\text{mT}$. These are moderate gradients. However the e-Linac application calls for cw operation at 2K so reducing the active load in each cavity is important. The active load is dependent on the cavity gradient and the quality factor using:

$$P_{cav} = \frac{V^2}{R/Q \cdot Q} \text{ where } V = E_a L \text{ is the effective cavity}$$

voltage, R/Q is the characteristic shunt impedance of the cavity and Q is the unloaded quality factor. In order to reduce the active load at 2K the cavity is specified to operate at an unloaded Q_0 of $1e10$. This would produce an active load of 10W per cavity. Table 1 shows characteristic parameters for the cavity as applied to the e-Linac requirements. The cavity Q is related to the global surface resistance, R_s , and the geometric factor, G , by the relation $G=Q/R_s$.

Table 1: RF Parameters for the Tesla Cavity Applied to the e-Linac

Parameter	Units	Value
Frequency	GHz	1.3
V_{eff}	MV	10
L	m	1.0
R/Q	Ohms	1030
G	Ohms	280
E_p/E_a		2.0
H_p/E_a	Oe/(MV/m)	43
Q_0		$1e10$
P_{cav}	W	10

The surface resistance is determined by a temperature and frequency dependent term, R_{bcs} , a term due to flux trapping from the background magnetic field, R_{mag} , and a residual term, R_0 , due to the quality preparation of the cavity surface. The total surface resistance and associated terms are given by

$$R_s = R_{bcs} + R_0 + R_{mag} \text{ where for niobium at } T < T_c/2$$

$$R_{bcs} (\Omega) = 2 \times 10^{-4} \frac{1}{T} \left(\frac{f(\text{GHz})}{1.5} \right)^2 \exp\left(-\frac{17.67}{T}\right) \text{ and}$$

$$R_{mag} (\text{n}\Omega) = 0.3 H_{ext} (\text{mOe}) \sqrt{f(\text{GHz})}$$

To operate at $Q_0=1e10$ the multi-cell cavity of Table 1 would have to operate with an average surface resistance of $R_s=28\text{n}\Omega$. Given that for a 1.3GHz cavity operating at

a temperature of 2.0K and a background field of 15mOe $R_{bcs}=10.9\text{n}\Omega$ and $R_{mag}=5.1\text{n}\Omega$, the residual resistance is required to be $R_0 \leq 12\text{n}\Omega$ to meet this quality factor. The relation between achieved quality factor and average R_0 are plotted in Fig. 3. For comparison at $E_p=20\text{MV/m}$ the twenty cavities for ISAC-II Phase I have an average surface resistance of $R_0=9\text{n}\Omega$ while the ISAC-II Phase I cavities have an average surface resistance of $R_0=34\text{n}\Omega$. The chief difference between the two cavities besides the fabrication/processing source is that the Phase I cavities received $>120\mu\text{m}$ of surface etch while most of the Phase II cavities were limited to $60\mu\text{m}$ etching [5]. This motivates the etching studies on the 1.3GHz cavity reported below.

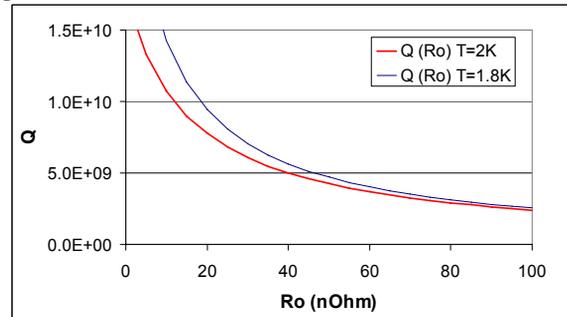


Figure 3: The quality factor in a 1.3GHz elliptical cavity as a function of residual resistance for operation at 2.0K (and 1.8K) and a background field of 15mOe.

Cavity Design

Presently the design baseline is to use a modified nine cell with inner cells very similar to the Tesla shape but with end tubes to 96mm diameter designed for the large power coupler ports of 62mm and to mitigate HOMs. Preliminary HOM studies and beam dynamics considerations have shown that the BBU threshold is above 30mA when the shunt impedance of the dipole modes are $R_{q/Q} \cdot Q_L \leq 10^7 \text{Ohm}$. A complete scan of a full length model with $1/4$ azimuthal geometry and symmetry planes of H-H, H-E, E-H, E-E with $\sim 450,000$ mesh cells was done for a frequency band 0-3.25 GHz using the CST JDM solver with an accuracy of $1e-5$. Virtual damping was employed by applying resistive wall (stainless steel) conditions on the beam tubes 60mm in length starting 117mm from the entrance and exit iris. The damping tubes are effective in reducing the shunt impedance of many of the modes but some problematic modes are apparent. Initial undamped HOM data resulted in typical BBU threshold currents at 10-100 μA level. Damped data resulted in 3-30 mA threshold current depending on the phase of the horizontal betatron motion and the recirculation length. There is a trapped TE111 mode at 2.56GHz that is unaffected by the damping pipes with a shunt impedance of $2.5e7$ and a mode in the tuner end cell at 1.5GHz. Several paths are being pursued to reduce the shunt impedance of the problematic modes. They include modification with a slight asymmetry of the end cells, modification of the inner cell shape and increase of the iris diameter.

Cavity Fabrication

Cavity fabrication is being done in collaboration with PAVAC Industries of Richmond, BC. The cavities are formed from dies sourced through collaboration with FNAL. First forming and fabrication studies were done in copper. Several half cells have been formed. This established both the forming techniques but also the fixtures for frequency measurement and cell tuning. Two single cell cavities in niobium have been produced at PAVAC; TR-PAV-1 (Fig. 1) and TR-PAV-2. Cavity tests of TR-PAV-1 are reported below. Multi-cell cavity fabrication has begun with the fabrication of a 7-cell cavity in copper.

Cavity Processing: The cavity is received from the fabricator, leak and pressure tested, degreased and etched with BCP. The cavity is fitted with a Teflon flange and drain tube at the lower end, a fill tube and a teflon extension reservoir and overflow tube at the upper end. Coupons are used to measure the etch rate. Acid at 9°C is pumped into the cavity while cooling coils are positioned around the cavity neck to maintain the acid to <13°C. Etching is done for a prescribed time while periodically removing a quantity of polluted acid from the bottom of the cavity and refilling to maintain level. The cavity is then rinsed and reconfigured to allow etching the cavity in an upside down orientation to improve etch uniformity.

Etching History (TR/PAV-1): A 2-D model in COMSOL of the single cell cavity is used to estimate the frequency sensitivity to the amount of etching. The computed sensitivity is -13kHz/μm for a uniform removal. From previous experience with ISAC-II QWR it has been determined that the etch rate on the rf surface is less than the etch rate measured on a coupon due to the reduced acid flow near the surface. The reduction is as much as 30-50%. In the present case the frequency swing is ~30% less than that suggested by the model based on removal rates on the coupons. The following estimated etch amounts were completed prior to each of four cold tests; 63, 108, 29 and 72 microns for cumulative removal of 63, 171, 200 and 272 microns.

The etching/testing cycles parallel a similar development with the PAVAC/TRIUMF QWR's[7]. The goal is to determine the amount of etching required for optimum cavity performance and to determine the source of the hydrogen that has been identified as being a characteristic of the fabrication/processing to date. TRIUMF has not degassed the cavity at any stage in the fabrication to date due to the unavailability of a degassing chamber.

Cavity Testing: TR-PAV1 was tested both at 4K and 2K in a closed cycle with BCP processing between test steps. Each test is preceded by a 48 hour bake at 120C under vacuum. The Lorentz force detuning is -6.5 Hz/(MV/m)². From 4K-2K the pressure sensitivity is -140 Hz/Torr. Results of the 2K measurements are shown in Fig. 4. There is a steady improvement in the base Q₀ after each etching step. High field performance is limited in all cases. In Test 1 and Test 2 the field was limited by the subatmospheric pumping power. In Test 3 the cavity was

accidentally vented with unfiltered air prior to the test causing the premature onset of field emission. In Test 4 the base Q₀ reached the goal of 1e10 but a helium leak developed and the Q degraded strongly with rf field. At 4K the test 4 cycle achieved a field of 12.5MV/m without field emission and with the cavity performance limited only by available rf power. The helium leak was exacerbated by pumping to 2K and the performance at 2K was sharply affected by the poor vacuum. Each measurement was also accompanied by a warming step to >100K for ~1 hour to test the sensitivity of the cavity to Q-disease. RF characterization after this 100K treatment is shown in Fig. 4 for Test 1 and Test 2. The results indicate that even with the improved characterization from Test 1 to Test 2 the results after 100K soaking degrade to the same surface resistance in each case indicating no change in the hydrogen concentration. The cavity is being readied for the next test.

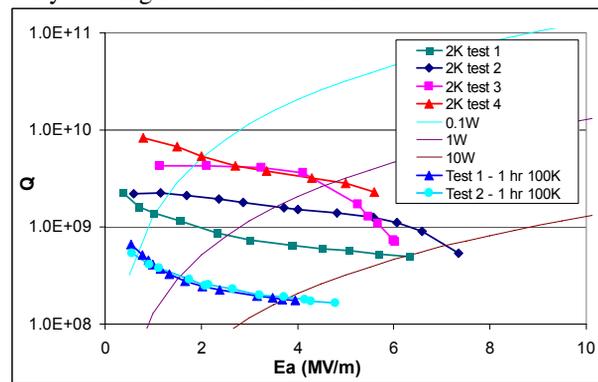


Figure 4: RF characterization curves for the cavity TR-PAV-1 at 2K after each of the four etch steps. Also shown are the 2K characterization curves after Test 1 and test 2 following a warming above 100K for 1 hour.

ACKNOWLEDGEMENTS

The authors would like to thank the expert technical assistance of the SRF and Vacuum/Cryogenic groups.

REFERENCES

- [1] S. Koscielniak, et al, "Electron Linac Photo-fission Driver for the Rare Isotope Program at TRIUMF", IPAC2010, Kyoto, Japan.
- [2] V. Naik, et al, "VECC/TRIUMF Injector for the e-Linac project", these proceedings.
- [3] Stanford, et al, "Engineering and Cryogenic Testing of the ISAC-II Medium Beta Cryomodule", LINAC2004, Lubeck, Germany.
- [4] R.E. Laxdal, "Initial Commissioning Results of the ISAC-II Linac", LINAC06, Knoxville, Aug. 2006.
- [5] R.E. Laxdal, et al, "Operating Experience of the 20MV Upgrade Linac", these proceedings.
- [6] V. Veshcherevich, et al, "A High Power CW Input Coupler for Cornell ERL Injector Cavities", SRF2003, Trevemunde, Germany.
- [7] D. Longuevergne, et al, "Experimental Study of the Surface Resistance of the 141 MHz Quarter-Wave Resonator at TRIUMF", these proceedings.