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DESIGN OF AN RF MODULATED THERMIONIC ELECTRON SOURCE AT TRIUMF

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Abstract

The electron source in the TRIUMF ARIEL project is a gridded dispenser cathode. The cathode is biased at -300 kV, and the grid requires a RF control signal of up to 200 V at 650 MHz. The required RF power is approximately 20 W and is provided by an RF amplifier located outside the gun vessel. This RF power is coupled into the gun circuit through a ceramic transmission line. The design of this ceramic transmission line, as well as the impedance transformation circuit, which provides both the impedance matching and the dc powers to the gun assembly, is described.

INTRODUCTION

The ARIEL e-Linac is required to produce a 50 MeV, 10 mA electron beam in order to reach the goal rate of 10^{14} fissions/second in actinide targets via the photo-fission process. The e-Linac will operate in Continuous Wave (CW) mode to avoid thermal cycling of the targets, which can lead to fatigue and failure of the targets. Acceleration is provided by five 9-cell 1.3 GHz superconducting cavities operating at 2 K, taking advantage of the global design effort towards high performance 1.3GHz superconducting RF cavities.

The electron source for the ARIEL eLinac, shown in Fig. 1, was developed at TRIUMF. The source is an RF modulated thermionic electron gun, operated at 650 MHz and producing bunch charges of 15.4 pC. This will provide a CW beam with 10 mA average beam current. With a cathode voltage of 300 kV, electrons from the source may be directly injected, after bunching, into the first 9-cell accelerator cavity in injector cryomodule.

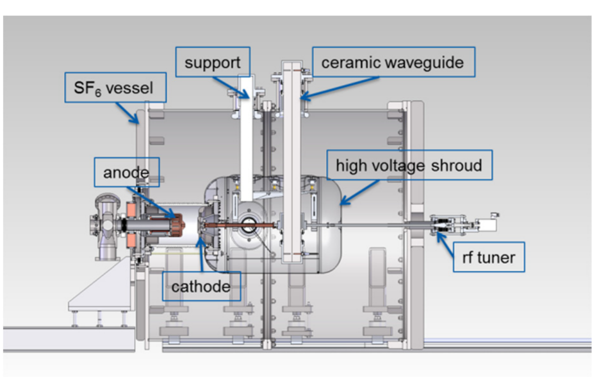

Figure 1: The electron source for the ARIEL eLinac.

The source cathode is separated from the anode by an Al_2O_3 ceramic voltage standoff, and the source is isolated from ground within a vessel filled with sulphur hexafluoride (SF_6) gas pressurized to 2 atmospheres. SF_6 is an excellent insulator and provides an increased breakdown voltage, reducing the necessary length of the cathode voltage standoff. The cathode is mounted on an interior high voltage enclosure which contains the RF power feedthrough and matching circuit. The shapes of the high voltage enclosure and feed-troughs have been designed to keep the electric fields below 25 kV/cm through the use of corona shields. The outer size of the vessel is 1.5 m in diameter and 1.7 m in length.

The electron source uses a thermionic triode, modulated at 650 MHz. The thermionic dispenser cathode is biased at -300 kV with respect to the anode at ground. The RF modulation is applied to a grid placed directly in front of the cathode to control the release of electrons from the cathode surface by the superposition of DC and RF voltages on the grid. Electrons are emitted from the cathode only when the grid voltage is greater than a cut-off voltage, allowing electrons to pass through the grid to be accelerated towards the anode. The voltage at the grid due to both DC and RF components is shown in Fig 2.

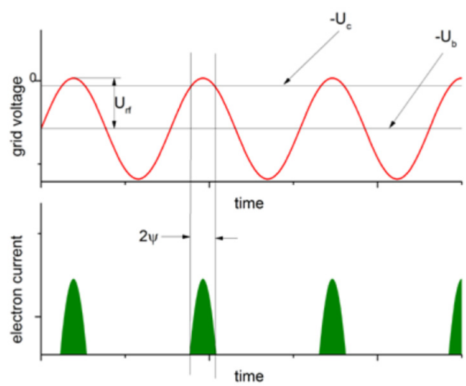

Figure 2: On the top, the time dependant voltage on the cathode grid. When the grid voltage is greater than the cut-off voltage –Uc, electrons are released, resulting in the electron current shown below.

IMPEDANCE MATCHING SECTION

The RF resistance at these operating parameters are calculated to be ~10 kΩ, labelled as R_G in Fig. 3. The cathode-to-grid capacitance is C_{GC}. The gun housing is a short triaxial line of characteristic impedance Z between the cathode and the grid, and a length of *l*. The centre conductor is the filament supply and is not used in the following calculations. The reactance for the coaxial gun (cathode-grid capacitance) and socket (short transmission line) used had been measured and best represented by a series 15 Ω transmission line of 29.52 mm length, labelled as ‘Gun socket’ in the Fig 4. A tuning section is used to convert the resultant complex impedance into real resistance, and then a 2-section ¼λ transformer converts this resistance to 50 Ω as shown in Fig 4. and the geome-

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try is shown in Fig. 5. The tuning section has a characteristic impedance of 95 Ω, which is determined by the diameter of the gun socket. The length is adjustable

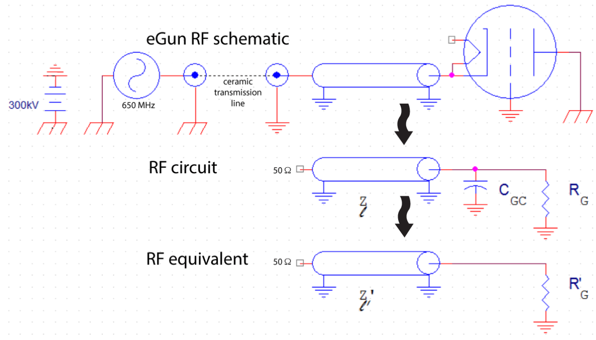

Figure 3: Circuit of the impedance matching section.

20 cm to 30 cm. This in effect forms a capacitance loaded ¼λ section where the gun's complex impedance is transformed to 0.195 Ω. To transform from 0.195 Ω to 16.5 Ω, the first ¼λ transformer section requires a characteristic impedance of 1.8 Ω. Such low impedance can only be achieved using dielectric-filled transmission line. Kapton is used as the dielectric, which has added advantage of the inner section being supported mechanically by the dielectric. The second ¼λ transformer section is an air section that has a characteristic impedance of 28.5 Ω, which transform the 16.5 Ω into 50 Ω. From then on it is a normal 50 Ω transmission line and a right angle bend. A high impedance ¼λ line continues straight on to provide cathode bias. The same assembly also provides additional filament supply via the inner most conductor of this triaxial structure.

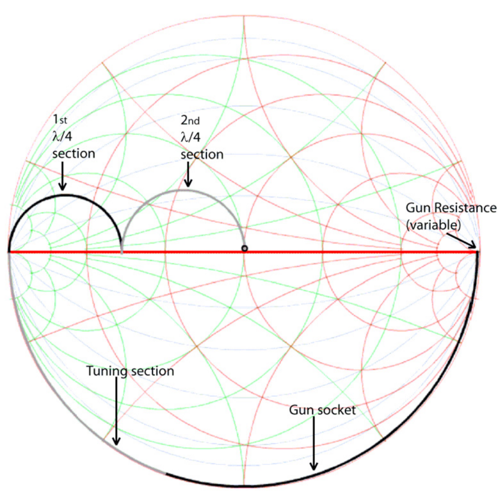

Figure 4: Smith chart of the impedance matching section.

CERAMIC WAVEGUIDE

The cathode assembly is biased at -300 kV, however it is preferable to have the RF power amplifier outside of the high voltage vessel and the LLRF control referenced to ground potential. This requires transporting the roughly 100W of RF power from amplifier to the electron source via an insulating transmission line. A dielectric (ceramic) waveguide is used because it has low insertion loss at the operating frequency of 650MHz while at the same time providing 300 kV DC isolation.

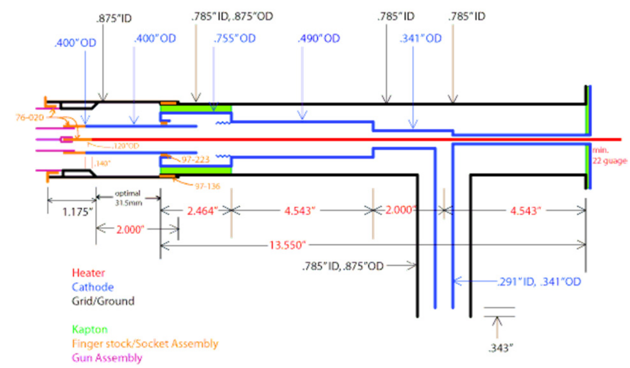

Figure 5: Geometry of the impedance matching section.

As shown in Fig. 6, the ceramic waveguide DC block consists of a cylindrical dielectric rod waveguide with mode converters on either end to transmit the RF power across an insulating gap. The mode converters launch and receive the RF power, resulting in low losses when correctly matched.

Figure 6: The ceramic waveguide showing the input/receiving antennas, matching sections, and the air/ceramic transmission line.

Within the launcher and receiver sections of the ceramic waveguide, the dielectric rod is enclosed by a conducting metal boundary and therefore acts as a metal-dielectric cylindrical waveguide. An Alumina (Al_2O_3) ceramic rod with dielectric constant 9.9 and a diameter of 105 mm has a cut-off frequency for the lowest transverse electric (TE) mode of $f_{TE_{11}} = 532$ MHz and a characteristic impedance $Z_g = 208$ Ω.

RF power is fed into the waveguide using a coaxial cable propagating a TEM wave with a characteristic impedance of 50 Ω. The side-launch method is used to convert the 50 Ω TEM wave into a 208 Ω TE11 wave. This method offers good performance and reasonable bandwidth, but limited capability for tuning. A short, capacitive antenna is inserted into the side of the waveguide. For optimal matching, the probe back distance is slightly shorter than $\frac{1}{4}\lambda_g$ from the shorted end and the probe depth is slightly shorter than the radius of the waveguide. Using the 3-dimensional electromagnetic simulation tool HFSS, the optimized probe back distance is 50mm or $0.195\lambda_g$, and the probe depth within the waveguide is 43mm. This results in almost perfect matching from 50 Ω to the waveguide impedance at 650MHz. The insertion loss at 650 MHz is 0.5 dB, primarily due to losses within the ceramic.

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A break in the metal covering on the waveguide is required to provide an insulating gap for the 300 kV dc bias. The dominant mode in an air-dielectric waveguide is the hybrid HE_{11} mode. The electric and magnetic fields within the waveguide leak out into the space surrounding the dielectric rod as evanescent wave. Since the electromagnetic fields in the regions close to the ceramic surface are non-zero, objects in close proximity to the waveguide can perturb the fields, resulting in increased transmission losses.

Because of the non-zero boundary conditions at the air-ceramic interface, this mode does not have a lower cut-off frequency nor does it have an analytical solution in closed form[1,2]. We therefore cannot calculate analytically the characteristic impedance for this waveguide. The impedance should however be bounded between the impedance of the metal-ceramic waveguide, 208 Ω, and of free space, 377 Ω. For a high dielectric constant, the true value should be closer to 208 Ω.

A pair of ¼λ transformers in the form of choke horns is used to match the TE_{11} mode present in the metal-ceramic portion of the waveguide to the HE_{11} mode in the insulating gap. The geometry of the choke-horns has been optimized using HFSS to optimize the transmission and bandwidth at 650 MHz.

PERFORMANCE

The design of the dielectric waveguide was studied using HFSS, based on the double choke-ring mode converter for the launching and receiving sections, as depicted in Fig. 7.

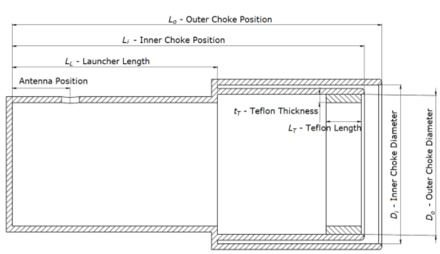

Figure 7: Double-ring choke horn geometry.

The dielectric medium is a 105 mm diameter rod of low loss, 99.5% pure alumina ceramic, with a dielectric constant of 9.9 from Kyocera. A Teflon spacer was included between the first choke ring and the dielectric to insure the centering of the choke horns around the dielectric. For installation into the 300 kV electron gun vessel, further optimization of the choke horns was necessary to account for features in close proximity to the waveguide, such as the high voltage corona shields. The re-optimized choke horns results in a design with an insertion loss of -3 dB at 650 MHz. The launching and receiving choke horns were optimized independently to account for asymmetries on either end of the waveguide. The new choke horns' geometry included a larger gap between the first choke ring and the dielectric in order to lower the peak electric field on the tip of the inner choke ring from the 300 kV DC potential. A dielectric spacer located in this gap again assists in the positioning of the choke ring, but also allows for in-situ tuning of the waveguide by varying the length and material of the spacer to achieve the optimal transmission at 650 MHz.

The transmission curve measured from the waveguide installed into the eGun vessel is shown in Figure 8. The insertion loss at 650 MHz was measured to be 1.7 dB, which is better than the simulated value of 3 dB. This corresponds to almost 80% of the incident RF power being transmitted across the waveguide to the electron source.

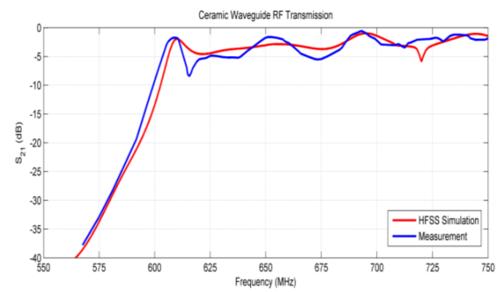

Figure 8: Comparison of the measured transmission across the ceramic waveguide, installed in the eGun vessel, to the transmission simulated in HFSS.

The 300 keV electron source has performed for over 2 years with the dielectric waveguide with no issues related to the waveguide encountered. Because of the high efficiency of the matching section and the ceramic transmission, we have been able to operate the eGun at less than 20 W of rf power from the final rf amplifier.

CONCLUSION

A novel method for supplying RF power to an electron gun cathode grid, across a high DC potential difference has been described. The dielectric waveguide transmits RF power though an insulating dielectric rod, guided by a launcher and receiver mode converters on either end of the dielectric. The design of the dielectric waveguide for TRIUMF's ARIEL eLinac electron gun has been described. The waveguide was optimized using simulation tools, resulting in a design that when implemented, exceeded performance expectations.

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