A SUPERCONDUCTING RF DEFLECTING CAVITY FOR THE ARIEL e-LINAC SEPARATOR

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Abstract

A 650 MHz SRF deflecting mode cavity has been designed for the ARIEL e-Linac to separate interleaved beams heading towards either Rare Ion Beam production or a recirculation loop for energy recovery, allowing the e-Linac to provide beam delivery to multiple users simultaneously. The cavity geometry has been optimized for the ARIEL specifications, resulting in a very compact cavity with high shunt impedance and low dissipated power. Analyses have been performed on the susceptibility to multipacting, input coupling considering beam loading and microphonics, and extensive studies into the damping of transverse and longitudinal higher order modes. The pressure sensitivity, frequency tuning, and thermal behaviour have also been studied using ANSYS. The cavity design resulting from these considerations will be discussed here.

INTRODUCTION

The ARIEL e-Linac is a MW class CW electron linear accelerator being constructed at TRIUMF to produce a 50 MeV, 10 mA electron beam for the production of rare isotopes to expand TRIUMF's Rare Isotope Beam (RIB) experimental program. The electrons are accelerated in five 9-cell, 1.3 GHz superconducting accelerating cavities housed in three cryomodules. A single cavity in the injector cryomodule (EINJ) will boost the electrons from 300 keV to ~ 10 MeV, followed by the two accelerator cryomodules (EACA/B) for a final beam energy of up to 66 MeV.

A future extension of the e-Linac will be the construction of a recirculation loop that would return electrons to make a second pass through the two accelerating cryomodules. This layout could be operated as a Recirculating Linac (RLA) to double the energy of the electron beam, or as an Energy Recovery Linac (ERL). In this mode the electrons would return for a second pass through the accelerating cavities in the decelerating RF phase, resulting in the deceleration of second pass electrons and the return of their energy back to the accelerating cavities. This beam could be used to drive an infrared or THz Free Electron Laser (FEL) or x-rays through inverse Compton scattering in the back leg of the recirculation loop.

Bunches bound for either RIB production or the ERL would be interleaved, occupying adjacent RF buckets in the 1.3 GHz accelerating RF. This requires separating the bunches bound for either the ERL or RIB at the end of the linac at a frequency of 650 MHz. Due to the high frequency of separation required, an RF separator is required to impart opposing deflections to adjacent bunches. The concept of the RF separation scheme has been laid out in [1] which describes the layout and deflections required by each element in the separation complex: an RF deflecting cavity, steering dipole, defocusing quadrupole, and septum magnet, as shown in Figure 1. The recirculated and decelerated beam would make a second pass through the deflecting cavity in the zero crossing phase to be separated from the high energy beams by the dipole magnet.

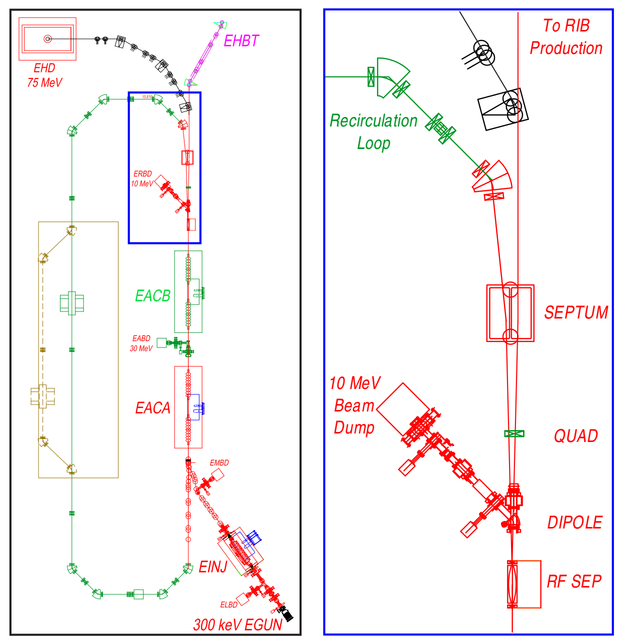

Figure 1: The ARIEL e-Linac and recirculation loop on the left and on the right, a magnified view of the separation complex.

CAVITY DESIGN

The geometry of the deflecting cavity was based on the RF Dipole [2] and Double Quarter Wave (DQW) [3] crab cavities being developed at ODU/JLab and BNL respectively. The deflection in this cavity is due to the electric field between two parallel ridge faces, with the magnetic field acting to decrease the net deflection. The cavity was optimized for increased transverse shunt impedance by reducing the magnetic field contribution to the deflection. This resulted in a "Post-and-Ridge" type design, Figure 2, where an undercut was added to the ridge to decrease the magnetic field density along the axis of the cavity. The overall length of the cav-

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ity was also minimized in order to reduce the longitudinal footprint of the cavity.

The resulting cavity design provides high deflecting fields within a compact cavity with low RF power dissipation. The cavity will operate at 4 K, taking advantage of the 4 K Helium supply available in the electron hall for the injector and accelerating cryomodules [4]. The RF properties of the cavity are summarized in Table 1. For the nominal operating voltage of 0.3 MV and operating at 4 K, the dissipated power will be approximately 0.2 W.

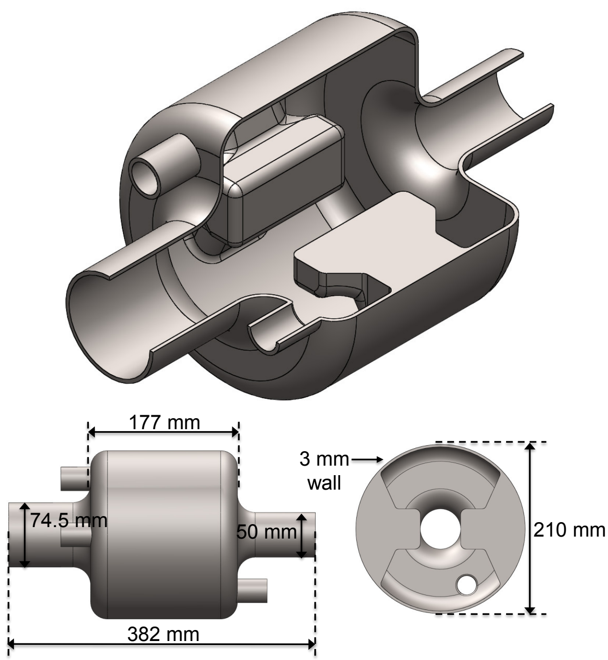

Figure 2: The ARIEL e-Linac RF deflecting cavity geometry.

Table 1: Properties of the RF deflecting cavity.

Parameter	Value	Units
Frequency of the operating mode	650	MHz
Frequency of the first HOM	935	MHz
Cavity length	177	mm
Cavity diameter	210	mm
Nominal (Max) cavity voltage, $V_\perp$	0.3 (0.6)	MV
Shunt Impedance, $R_\perp/Q$	625	Ω
Geometry Factor, G	99	Ω
$R_\perp R_s$	6.2×10^4	Ω^2
Peak electric field, E_p	9.5 (19)	MV/m
Peak magnetic field, B_p	12 (24)	mT

MULTIPACTING SUSCEPTIBILITY

Analysis of the cavity geometry using TRACK3P, a particle tracking code in the ACE3P suite of finite element codes, was performed to study its susceptibility to multipacting. Using the code, electrons launched from the cavity surface were tracked through 50 RF periods, identifying particles that get trapped in resonant trajectories. The impact energies of these resonant particles are plotted in Figure 3.

A low number of resonant tracks are seen below about 0.4 MV. The number of resonant trajectories starts increasing for deflecting voltages above this, and with it, an increasing chance of multipacting at higher voltages. Multipacting is not expected at the nominal operating voltage of 0.3 MV. Previous experience in cryogenic tests of the RF Dipole and DQW cavities showed some multipacting during initial cold tests, although these were fairly easily processed and were not seen again in later tests [3, 5, 6].

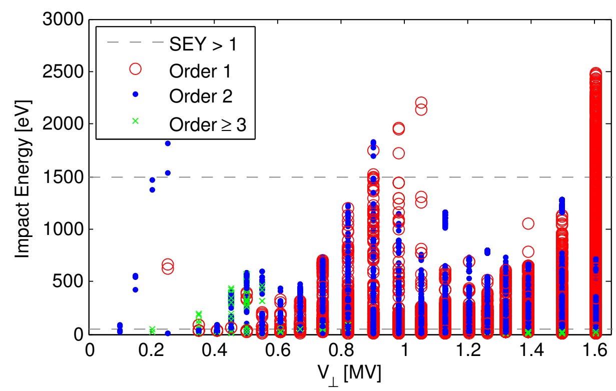

Figure 3: Electron impact energies of resonant tracks for discrete deflection voltages.

INPUT COUPLING

Input power will be provided by a coaxial input coupler located on the end cap of the cavity, on the horizontal plane. The coupler port runs parallel to the beam pipe, followed immediately by a 90° elbow to direct the path of the input coupler away from the beam pipe, as shown in Figure 4. The outer diameter of the input coupler is 24 mm.

Under normal operating conditions, less than 2 W of RF power will be dissipated on the tip of the copper inner conductor. This will be conductively cooled by a liquid nitrogen intercept located at the location of the vacuum feed-through. The temperature at the tip of a solid copper inner conductor would be expected to increase by about 10 K, while a hollow, 1 mm walled inner conductor would increase by 25 K. Less than 1 mW would be transferred to the cavity through radiative losses. With a transverse voltage of 0.6 MV, tip temperatures would increase by 40 to 100 K.

The cavity will be beam loaded only by a bunch which is offset from the beam axis and passing through the cavity in the zero crossing phase. This corresponds to only the recirculated ERL beam. The required input power, with and without microphonics detuning, is plotted in Figure 5 as a function of Q_{ext} for the nominal cavity parameters and a recirculated beam current of 20 mA. For typical beam currents and offsets, a Q_{ext} of 3×10^6 would result in minimal input power requirements. With no beam load or detuning, the minimum power required would be 15 W. In order to achieve

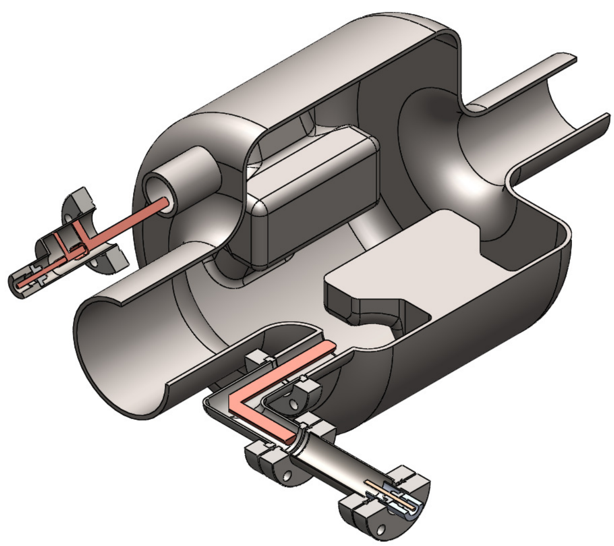

Figure 4: The input and HOM coupler concepts with the input coupler showing a 90° bend immediately after leaving the cavity, and the HOM coupler (retracted) on the top left showing the features of the notch filter.

a transverse voltage of 0.3 MV for 20 mA of recirculated beam offset by up to 2 mm, a maximum of ~ 200 W would be required.

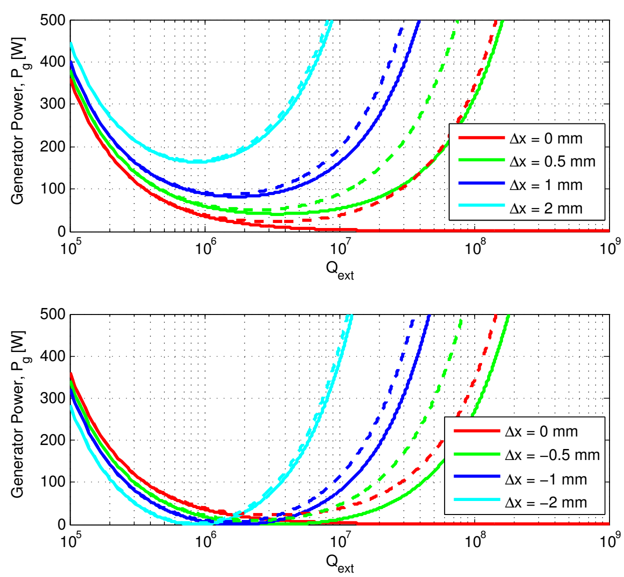

Figure 5: The required power to maintain 0.3 MV deflecting voltage with 20 mA of recirculated beam and 0 Hz (solid lines) or 100 Hz (dashed) of frequency detuning. The top plot is with beam loading removing energy from the cavity, and the bottom plot with energy driven into the cavity by the beam.

HIGHER ORDER MODES

Higher Order Modes (HOMs) can be excited by the beam when it passes through the cavity, leading to degradation and loss of the beam or a large amount of energy transferred into the cavity. For the ARIEL e-Linac, the required damping of transverse HOMs is defined by the multi-pass beam break up effect, where multiple passes of the same bunch in the cavity can lead to exponential growth of HOM intensity through positive feedback. The goal shunt impedance was taken as a factor of 10 less than the threshold limit under worst case conditions, and was found to be approximately $R_{\perp}/Q \cdot Q_L < 1 \times 10^6\,\Omega$.

For longitudinal modes, a large amount of power may be dissipated by HOMs resonant with the bunch repetition rate. Resonant machine lines exist at multiples of 650 and 130 MHz, the latter being the likely bunch frequency of the ERL beam. To limit the power that may be dissipated, HOMs require sufficient damping as well as avoiding frequencies near the machine lines. Transverse modes may also dissipate energy in the cavity but require an offset from the cavity axis in order to couple to beam. The power dissipated is dependent on the transverse beam offset by a factor of $(\Delta x \omega_m / c)^2$.

HOM damping is achieved through both a dedicated HOM coupler and a stainless steel damper located in the beam pipe. The HOM coupler is mounted on the cavity endplate, on the same side of the cavity as the input coupler, as shown in Figure 4. The coupler consists of a coaxial antenna with a notch filter to block transmission of the operating mode at 650 MHz. An N-type vacuum feedthrough is used to transfer power out of the cryomodule for dissipation. In HFSS simulations, the operating mode filter has excellent transmission characteristics at frequencies above 1 GHz and drops to below -50 dB with a width of roughly 20 MHz at the operating frequency, as seen in Figure 6.

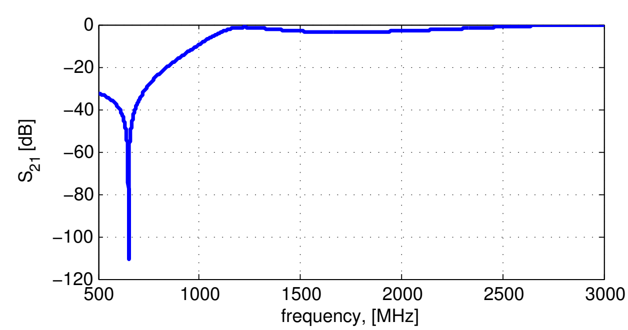

Figure 6: The simulated transmission spectrum of the HOM coupler with a 650 MHz notch filter. The first HOM has a frequency of 935 MHz.

The tip of the HOM coupler will extend a few mm into the cavity, resulting in some power dissipation on the tip from the operating mode. This amounts to less than 0.1 mW with a superconducting niobium inner conductor. In order to ensure the tip remains superconducting, the inner conductor will be cooled by a 4 K Helium cooling loop located at the base of the inner conductor, resulting in a temperature rise of the coupler tip of less than 0.5 K.

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Most modes below 3 GHz will couple to the HOM coupler, but a few rely on the beam pipe absorber. This is comprised of a stainless steel insert located in the 75 mm diameter beam pipe cooled by liquid nitrogen. The cut-off frequency of the beam pipe is 2.3 GHz, resulting in isolation of the operating mode with an external Q of 10^{10}.

The shunt impedances of the transverse and longitudinal modes damped by the HOM coupler and stainless steel damper were optimized in HFSS. All transverse modes were calculated to be at or below the goal shunt impedance, Figure 7. The power dissipated by the longitudinal HOMs is less than 1 W, and most modes are far from the nearest 130 MHz resonance, as seen in Figure 8. The red circles are the power at the simulated HOM parameters, and the solid line shows the effect of a HOM frequency error.

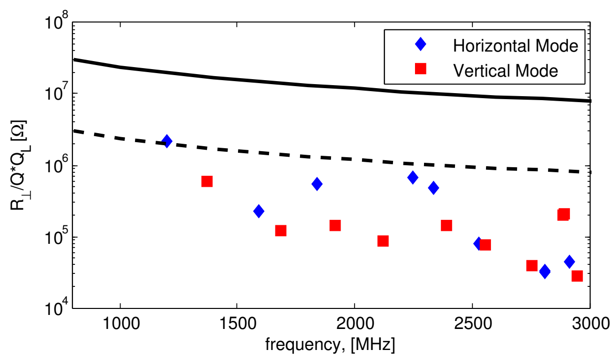

Figure 7: The HOM spectrum for transverse modes with the solid black line showing the shunt impedance limit and the dashed line as the goal shunt impedance.

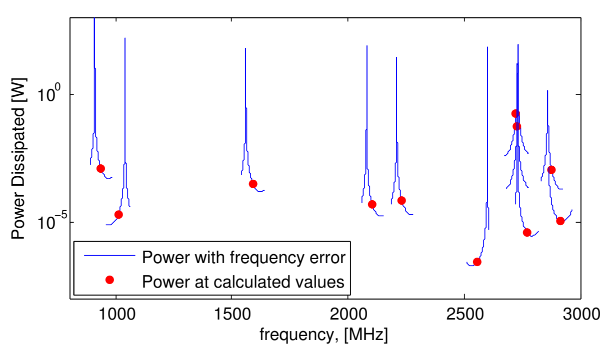

Figure 8: The power dissipated in longitudinal HOMs.

MECHANICAL CONSIDERATIONS

Experience with TRIUMF's ISAC II cryomodules which operate at 4 K shows about 2 mbar fast pressure oscillations. With a Q_L of 3×10^6 and a bandwidth of 220 Hz, a cavity pressure sensitivity of less than 10 Hz/mbar is required to keep the frequency error within 10% of the bandwidth.

The pressure sensitivity of the cavity has been evaluated using ANSYS APDL. A bare cavity, fabricated from 4 mm Niobium sheet will have $df/dp = -80$ Hz/mbar. This is due to the high sensitivity of the resonant frequency to the inner ridge position. The pressure forces the inner ridges inwards, decreasing the cavity frequency. It would take substantial stiffening plates added to the inner ridge to decrease the frequency sensitivity enough to reach the goal sensitivity.

Fabricating the inner ridge out of a solid Niobium instead will provide the required cavity stiffness to decrease the pressure sensitivity down below the goal level, as well as simplifying fabrication. With a solid ridge and 3 mm cavity walls, df/dp drops to roughly 1 Hz/mbar. The maximum stress intensity in the cavity reaches 15 MPa at 1 atm of external pressure, which is well below the Niobium's yield strength at both room and cryogenic temperatures.

Tuning of the cavity will be achieved by a scissor tuner applying a longitudinal force to the cavity in tension only. The tuning sensitivity of the cavity is roughly -380 kHz/mm with a stiffness of 5.4 kN/mm. For a tuning range of 400 kHz at cold temperatures, the maximum stress on the cavity would be roughly 270 MPa.

The tuner will grasp the cavity by the outer rim of the helium jacket, to keep clear of the input and HOM couplers located on the cavity endplate. Bellows will be installed on the Helium jacket and between the jacket and coupler ports to avoid twisting the cavity as it is tuned due to the non-symmetric port locations.

CONCLUSION

An SRF deflecting mode cavity has been designed capable of providing up to 0.6 MV transverse voltage at 650 MHz. This cavity has a compact size, low peak surface fields, and efficient operation at 4 K. The shunt impedances of the transverse modes are sufficiently damped to avoid multi-pass beam breakup and longitudinal modes are damped such that the maximum total dissipated power from all modes is less than 1 W, coupled to either a HOM coupler with operating mode filter or a stainless steel beam pipe absorber. This cavity will be installed in the ARIEL e-linac to enable simultaneous delivery of beams to both RIB production in the ARIEL facilities and the ERL.

REFERENCES

[1] Y. Chao, S.R. Koscielniak, and C. Gong, "RF Separator and Septum Layout Concepts for Simultaneous Beams to RIB and FEL Users at ARIEL," IPAC'11, San Sebastian, Spain, WEPC002 (2011).

[2] S.U. De Silva and J.R. Delayen, Phys. Rev. ST Accel. Beams 16, 012004 (2013).

[3] Xiao, B., et al, Phys. Rev. ST Accel. Beams 18, 041004 (2015).

[4] I. Bylinskii et al, "Particularities of the ARIEL e-Linac Cryogenic System," IPAC'15, Richmond, VA, USA, WEPMA005 (2015).

[5] S.U. De Silva and J.R. Delayen, Phys. Rev. ST Accel. Beams 16, 082001 (2013).

[6] A. Castilla, HyeKyoung Park, and J. R. Delayen, "Cryogenic Test of a 750 MHz Superconducting RF Crabbing Cavity," IPAC'14, Dresden Germany, WEPRI077 (2014).