BEAM DYNAMICS DRIVEN REQUIREMENTS ON THE ARIEL E-LINAC SRF SEPARATOR CAVITY*

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Abstract

A possible future extension to TRIUMF's ARIEL e-linac is the addition of a recirculation path for an Energy Recovery Linac (ERL), which will drive an Infrared or THz Free Electron Laser (FEL). The ERL electron beam will be interleaved with the single-pass beam bound for Rare Isotope Beam (RIB) production in the ARIEL facilities, allowing for simultaneous beam delivery to both FEL and RIB users. A superconducting RF separator will separate the beams at the exit of the linac at a frequency of 650 MHz in CW mode. After a second pass through the linac, the energy recovered ERL beam will pass through the separator cavity out of phase with the deflecting fields, and at a much lower energy, before continuing to a beam dump. Using the General Particle Tracer software, three-dimensional simulations of the beam dynamics of the passing beams have been performed to determine the requirements on the SRF separator's deflecting field uniformity. Operation of the FEL requires minimal emittance dilution of the ERL beam from the separator. This contribution describes the results of these studies and the requirements imposed on the SRF beam separator.

INTRODUCTION

The ARIEL e-linac will produce a 50 MeV, 10mA CW electron beam as the photo-fission driver for the production of neutron rich Rare Isotope Beams (RIB). This complementary RIB source will expand TRIUMF's existing ISAC experimental program. The electron beam is accelerated through an injector cryomodule to an energy up to 10 MeV, and two accelerating cryomodules (ACM) up to an energy of 50 MeV in cavities operating at 1.3 GHz [1].

A future phase will be the addition of a recirculation loop to return the electrons for a second pass through the main linac. This may be configured as a recirculated linac (RLA), accelerating the beam up to 75 MeV before continuing on for RIB production, or as an Energy Recovery Linac (ERL) with a Free Electron Laser operating in the back leg of the recirculation loop and interleaved with the RIB beam in the main linac.

Successful operation of the FEL depends on a low emittance beam, requiring minimal emittance dilution imparted during the separation of the beams at the exit to the main linac.

RF Separator Layout

Bunches bound for either RIB production or the ERL will have the same energy when reaching the separator section and will occupy alternating buckets of the 1.3 GHz accelerating RF. Separation of the bunches will then require RF separation at a frequency of 650 MHz at the exit of the main linac. Furthermore, the separator layout must also be compatible with the RLA operating mode, which will rely on the static magnetic separation of the two beams.

The basis of this separation scheme has been developed in [2] and comprises of an RF separator cavity imparting an initial differential transverse kick to the two beam types, followed by a steering dipole, a defocusing quadrupole to further enhance the separation, and finally a septum magnet to perform the final separation of the beams. This scheme is driven by rigid space constraints that require the full separation of the beams within a distance of about 3 m. The layout of the separation section of the e-linac is depicted in Fig. 1.

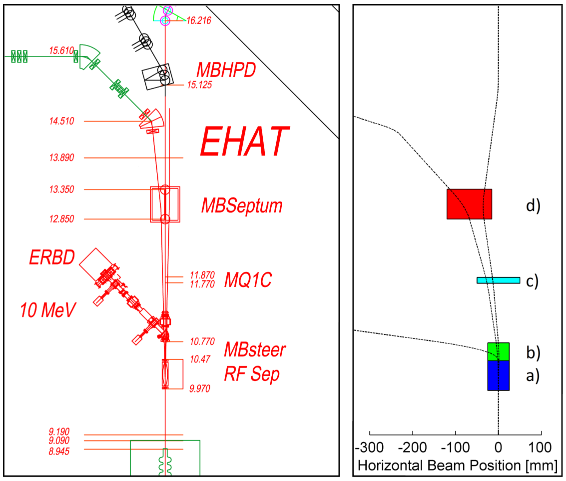

Figure 1: The layout of the ARIEL RF separator on the left with the beam deflections shown on the right. The elements shown are the a) RF separator cavity, b) dipole magnet, c) quadrupole, and d) septum.

In addition to the RIB and ERL beams, the decelerated beam after making its second pass through the ACM, will reach the RF separator with energy of 5 to 10 MeV and 90°out of phase with the cavities deflecting phase. It will therefore pass mostly unaffected through the separator cavity and receive a sharp deflection by the dipole magnet due to its low energy to be directed down a short transport line to a beam dump.

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An SRF cavity with RF Dipole geometry [3] is being considered for the RF separator. This cavity is compact in size and the transverse deflections are high with low peak electric and magnetic fields.

Beam Properties

The RF cavity will operate at 650 MHz to give opposing transverse momentum kicks to adjacent bunches from the main linac at ±90°. The required angular deflection imparted by the cavity is ±4.5 mrad for beam energies of up to 66 MeV and currents up to 16 mA CW.

The incoming RIB and ERL beams will have normalized emittances of 5 mm-mrad in both x and y and the transverse RMS beam widths on entering the RF separator cavity are 0.68 mm and 0.42 mm respectively, as determined from the e-linac optics. The energy spread of the beam will be around 0.5%.

After deceleration in the main linac, the beam will have an energy of 5 to 10 MeV with a significant energy spread of about 5%. Additionally, the bunch length will be quite long, up to 6.5 mm RMS.

TRACKING SIMULATION

The simulations of the beam dynamics were performed using the General Particle Tracer (GPT) [4] to quantify the emittance growth of the beam primarily within the separator cavity. The fields in the separator cavity, as described in [5], were exported from the HFSS RF simulation tool on a grid with 1 mm spacing [6]. GPT in turn uses this field map in an 8-point bilinear interpolation to evaluate the field at a specific point in space.

Bunches of 100,000 macro-particles were initiated immediately before the RF cavity with Gaussian spatial distributions and divergences scaled to obtain 5 mm-mrad emittances. The macroparticles were given a uniform distribution of energy spread about the mean beam energy of 50 MeV for the ERL/RIB beams and 7 MeV for the decelerated beam.

The tracking simulation through the RF cavity was performed with varying incoming beam parameters, different momentum kick strengths, and different cavity geometries to determine the emittance growth imparted by the cavity.

RESULTS

For the nominal beam parameters, the emittance growth in the horizontal direction was found to be very minimal with well under a 1% increase. The emittance in the vertical direction was found to be mostly unaffected by the RF cavity within the parameter space studied.

Sensitivity Studies

To investigate the impact of the RF separator cavity under non-optimal beam properties, the transverse and longitudinal RMS sizes, energy spread, and transverse position of the beam were varied about their nominal values.

The horizontal emittance was found to be most sensitive to changes in the transverse beam sizes, particularly in x direction, as shown in Fig. 2. The emittance growth stays below 1% for beam widths under 2 mm but grows very quickly for larger beams.

The emittance showed very little dependence on both the energy spread of the beam and the transverse position.

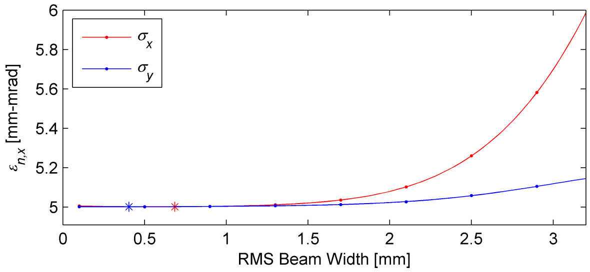

Figure 2: The normalized RMS transverse emittance, $\varepsilon_{n,x}$ at the exit to the RF separator cavity for different beam widths, for an RF voltage of 0.3 MV. The nominal beam widths are marked by the * symbol.

Increased Momentum Kick

Due to the limiting space within the TRIUMF E-Hall, a larger momentum kick imparted by the RF separator could achieve the separation of the beams in a shorter distance. This is desirable as it would loosen space requirements on the surrounding beam-line by allowing a shorter distance between the separator cavity and septum.

Increasing the transverse voltage of the RF cavity will amplify its effect on the emittance of the beam. This effect was studied with increasing deflecting voltages from the nominal 0.3 MV up to 1.7 MV for a 25 mrad angular deflection. This is nearing the upper limit of this cavity geometry with the peak fields approaching operational limits.

At the nominal beam parameters, minimal emittance growth is seen up to the maximum kick strengths studied, with the horizontal emittance increasing by less than 0.5%. Again, the emittance growth sees the largest correlation with the width in the x direction, as shown in Fig. 3. The emittance growth also shows a dependence on σ_y, bunch length, and shows a growing dependency on the y position of the beam.

Based on these results, the deflecting voltage of the cavity may be increased to approximately 0.7 MV, after which the emittance would become too sensitive to the beam width in the x direction. This corresponds to angular deflections after the separator cavity of up to around 10 mrad.

Field Uniformity

The main source of emittance dilution when passing through the separator cavity is the non-uniformity of the fields across the aperture, which causes beam particles to receive a different momentum depending on their transverse position. One way to achieve more uniform deflecting fields is to modify the geometry of the inner ridges of

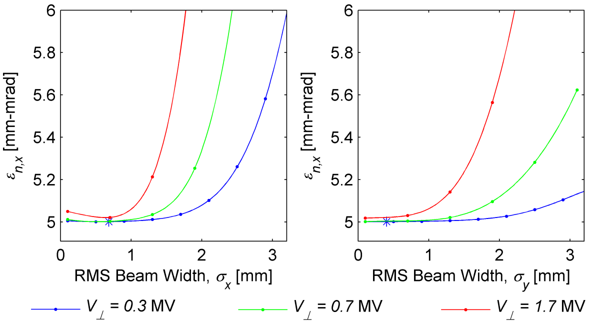

Figure 3: The normalized RMS transverse emittance, $\varepsilon_{n,x}$ at the exit to the RF separator cavity for different beam widths and varying momentum kick from 0.3 MV to 1.7 MV.

the RF dipole cavity to shape the fields in a more uniform way.

The cavity considered thus far has flat inner ridges, as shown in Fig. 4. By giving the inner ridges a slight outwards curvature, the field uniformity can be greatly increased with little effect on the RF properties of the cavity.

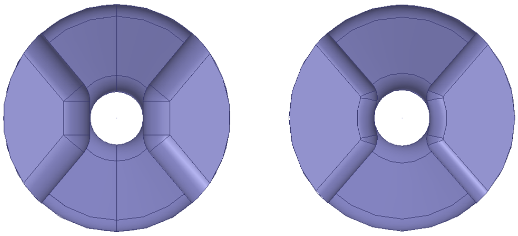

Figure 4: The cross section of the separator cavity with flat inner ridges on the left and curved ridges on the right.

In Fig. 5, the cavity with curved ridges contributes to the emittance growth similarly to the flat ridged cavity for RMS beam sizes less than 1.5mm, after which the curved ridge cavity results in lower emittance growths.

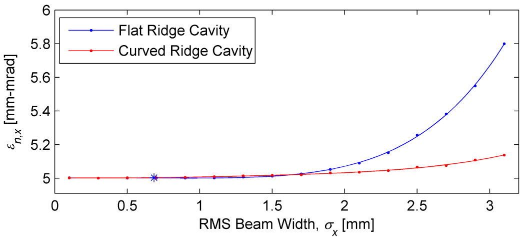

Figure 5: The normalized emittance, $\varepsilon_{n,x}$ at the exit to the RF separator cavity for the two different cavity geometries.

Decelerated ERL Beam

The decelerated beam passes through the RF separator cavity at the zero crossing, nominally with no deflections. However, as the bunch enters the cavity it sees the decreasing deflecting fields, imparting a small momentum to the bunch. While exiting, it sees the fields increasing again and receives an opposing kick. This results in a net zero angular deflection, but also a small horizontal deflection at the exit of the cavity. Additionally, since the bunch length of the decelerated beam is quite long, the head will see a small net angular deflection in the opposite direction as the tail, resulting in a small defocusing effect on the beam.

The scale of the horizontal deflection is approximately 0.5 mm for a 0.3 MV transverse deflecting voltage. This scales linearly with kick strength, resulting in a maximum offset of 2.5 mm for the highest kick strengths considered here, 1.7 MV. The defocusing effect was also found to be minimal.

Deflections of this size will not impede the safe passage of the decelerated beam through the separator cavity and dipole magnet without losing particles along the way. Quadrupoles located after the dipole along the dump beam line will ensure safe transport of the beam to the 10 MeV beam dump, located another 2 m past the separator cavity. The effect of the decelerated beam therefore does not impose any further requirements on the RF cavity.

CONCLUSION

These studies indicate that operating with nominal beam properties, the RF separator cavity will impart minimal emittance growth to the ERL and RIB bound beams. The beam width in the x direction contributes the largest to emittance dilution and for a cavity with flat inner ridges, RMS beam widths of under 2 mm will limit the emittance growth to less than 1%. Overall, the beam dynamics do not imply any stringent requirements on the RF separator cavity.

The upper limit to the deflecting voltage of the cavity is approximately 0.7 MV, after which with the emittance becomes very sensitive to the transverse beam width. This corresponds to a ±10 mrad angular deflection by the RF cavity. This sensitivity may be decreased by using a cavity with better field uniformity such as one with curved inner ridges.

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