LONGITUDINAL EMITTANCE MEASUREMENT SYSTEM FOR THE ARIEL ELECTRON LINAC

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Abstract

As part of the ARIEL e-LINAC project at TRIUMF, a 1.3 GHz single-cell, room-temperature deflecting cavity has been developed to study the temporal distribution of an electron beam from a 300 kV thermionic gun. Beam bunches on the order of 100-200 ps long are produced from a biased grid with a 650 MHz RF voltage superimposed to periodically allow release of electrons. The RF deflector operates in a TM110-like mode, deflecting the electrons vertically with a magnitude dependent on their arrival phase. The cavity RF performance has been characterized through signal level and beam testing. The deflector is installed as part of a longitudinal emittance measurement system with beam collimation, a 90 degree analyzing magnet, the deflecting cavity and a final view screen. Initial beam bunch length measurements using this RF cavity, conducted in conjunction with the initial commissioning using a 100kV electron-gun and a 1.3GHz buncher, are presented. The beam bunch length was extracted by comparing data collected at a screen downstream of the deflector to an analytical model based on linear time-invariant system theory.

INTRODUCTION

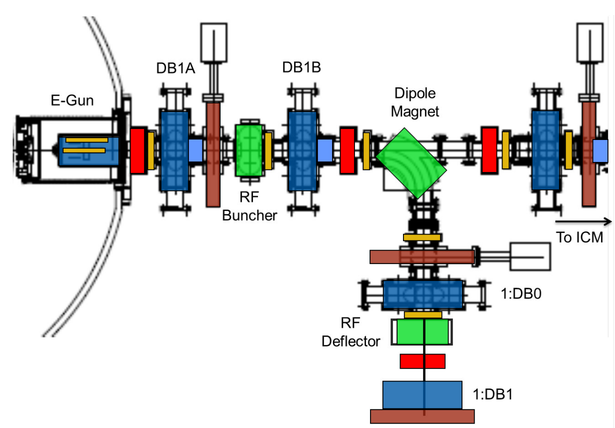

Figure 1: Low Energy Transport Line in the VECC Test Area.

The ARIEL project at TRIUMF is well under way, including a 50MeV linear accelerator using 1.3 GHz superconducting technology to accelerate a 10mA electron beam. TRIUMF is currently developing a 10MeV injection line for this electron linac in collaboration with the Variable Energy Cyclotron Center (VECC). A test area has been set up in the ISAC II building to commission various beamline components before installation in the ARIEL injection line and in Kolkata. The VECC Test Area consists of a 100kV (now 300kV) thermionic e-gun with an RF modulated gridded bias on the cathode at 650MHz, a low energy beam transport (LEBT), an injector cryomodule with a 1.3GHz superconducting 9 cell cavity, and a medium energy beam transport. Electron bunches ranging from 100-200ps long are emitted at a 1kHz repetition rate with a duty factor between 0.1% and 100%.

The LEBT section, pictured in Fig. 1, contains various beam diagnostics including linear profile monitors (LPMs), faraday cups, YAG screens and non intercepting beam profile monitors. The LPM consists of a vertical slit, horizontal slit and collimating hole which can be scanned across the beam to sweep the beam profile or inserted into the beam to select a beam profile.

THE LONGITUDINAL EMITTANCE MEASUREMENT SYSTEM

As part of the LEBT diagnostics, a longitudinal emittance measurement system was designed. It consists of an RF bunching cavity, dipole magnet, RF deflecting cavity in a 90° analyzing leg and downstream screen. The RF buncher manipulates the bunch length at a point downstream by accelerating late electrons in the bunch and decelerating early electrons. The dipole bends the beam into the analyzing leg, mapping the electron energy to the x axis through the dependence of the radius of curvature on electron energy, $\rho = \frac{\gamma \beta E_0}{qBc}$.

Circular apertures of 2mm diameter at the diagnostic boxes DB1A and DB1B (see figure 1) are used to limit the transverse emittance. The dipole magnet horizontal focusing is designed so an object at DB1B forms a dispersed focus at 1:DB0, such that a slit at 1:DB0 will select an energy slice of the beam.

In the analyzing leg, a 1.3GHz room temperature RF deflecting cavity maps the time spread of the beam to the vertical axis using E_y and B_x fields. A screen at 1:DB1 images the beam in the transverse plane. Using the deflector in conjunction with the dipole magnet, the beam energy and time spread can be extracted from the horizontal and vertical beam size, respectively. A solenoid upstream of 1:DB1 can be used to focus the beam at 1:DB1 with the RF devices off, producing a slight rotation of the $\Delta E/\Delta t$ (x/y) reference frame.

THE RF DEFLECTOR

The 1.3 GHz single cell deflecting cavity has been designed to analyze the temporal distribution of an electron

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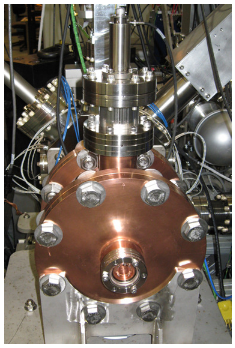

Figure 2: The deflecting cavity during installation.

beam bunch. The cavity is located in the analyzing leg of the injector line, as shown in figure 1. Pictured in Fig. 2, the cavity was designed after the Cornell deflector [1]. Similar in shape to a pillbox cavity, nose cones at the beam entrance and exit strengthen the on axis transverse fields. The cavity is operated in a TM_{110} like mode, resulting in a vertically deflected beam with the magnitude of deflection a sinusoidal function of the arrival phase of the electrons. Through CST simulations, for a β=1 particle the expected $\frac{R_\perp}{Q} = \frac{V_\perp^2}{\omega U}$ and transit time factor, T_0, were 930Ω and 0.51, respectively. $V_\perp$ is defined in equation 1, differing from a traditional potential to account for the effect of the magnetic fields on the beam.

$$V_\perp = \left| \int_{-\infty}^{\infty} c\beta B_x(z) e^{\frac{ikz}{\beta}} - iE_y(z) e^{\frac{ikz}{\beta}} \mathrm{d}z \right| \quad (1)$$

Signal Level Measurements

The deflector was manufactured at TRIUMF and after assembly and quality factor optimization, signal level measurements were conducted. While the quality factor of the cavity was 8800 before ultrasonic cleaning, close to the simulated value of $Q = 9766$, it is believed that soap residue has caused the current low quality factor of 5400.

The electromagnetic fields in the cavity were confirmed experimentally using the beadpull method. Magnetic fields on axis necessitated using both a dielectric and metallic bead. The dielectric bead only perturbs the electric field which can then be subtracted from the total perturbation with the metal bead to obtain the magnetic fields.

The results of the beadpull are shown in figure 3, normalized to emphasize the difference in field shape. Compared to simulation, the peaks of the experimentally determined fields are narrower. This is due to a slightly different nose cone length than in the CST model. As a result, the transit time factor of the cavity is increased and for $v = c$, T_0=0.56 $\pm$ 0.03. The effective shunt impedance of the cavity is smaller than expected though, with an $\frac{R_\perp}{Q}$ of 120 $\pm$ 10 Ω, 390 $\pm$ 20 Ω and 710 $\pm$ 30 Ω for a particle with a β of 0.51, 0.78, and 1 respectively.

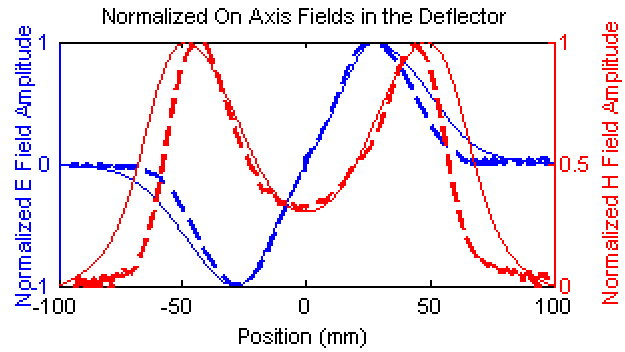

Figure 3: Fields along the beam axis of the deflector. The dashed line corresponds to the experimentally determined fields while the solid line corresponds to simulation.

Beam Loaded Measurements

Beam loaded commissioning of the cavity began in September, 2012, in conjunction with the commissioning of the LEBT section and 100keV e-gun [2]. The beam was bent into the analyzing leg using the dipole magnet, and images of the beam were taken using the screen at 1:DB1.

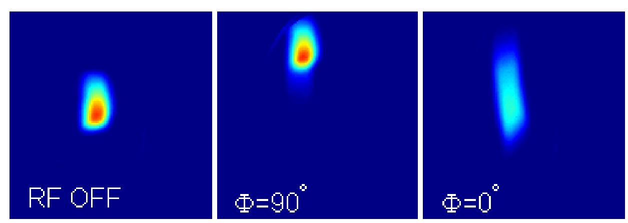

Figure 4: The effect of the deflector on the beam.

Turning on the deflector and scanning the RF phase produces a noticeable effect on the beam, even at low input powers. Figure 4 shows the effect of the deflector at an input power of 21W and RF phases of 90° (maximum centroid deflection) and 0° (diagnostic phase). The deflector imparts a vertical deflection to the beam given by $\frac{\Delta y}{\Delta z} = \frac{V_\perp}{\beta^2 E_T}$ where E_T is the total beam energy.

By measuring the maximum deflection at several deflector power levels, the deflector effective voltage can be obtained using the above equation. Figure 5 shows a plot of the deflecting voltage versus input power from which an effective shunt impedance of 0.71$\pm$0.05 MΩ was obtained. This agrees with the expected $R_\perp$ for a $\beta = 0.51$ electron of 0.65$\pm$0.03 MΩ from the beadpull.

INITIAL MEASUREMENTS

With the deflector commissioned, initial longitudinal emittance measurements have been conducted. By inserting the vertical LPM slit at DB1B, all particles have the same initial horizontal position. Their final position at the screen on 1:DB1 is thus, to first order, only a function of the particle energy and time of arrival at the deflecting cavity for a constant deflector power.

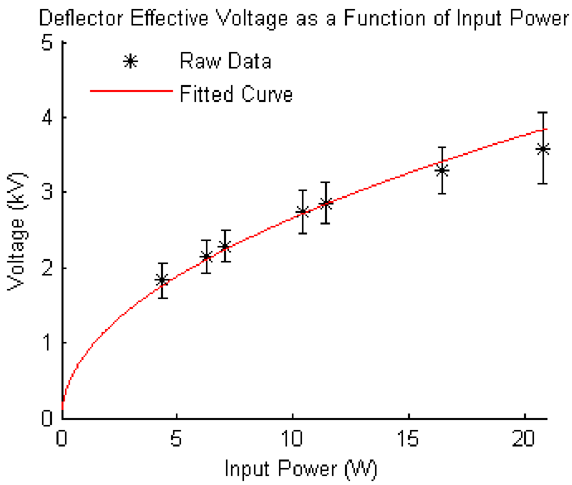

Figure 5: The effective voltage of the deflecting cavity.

The time spread is calibrated by sweeping the deflector from 0 to 360°. Comparing the maximum spread at the diagnostic phase (0°) with the maximum centroid deflection (±90°), the bunch length in RF degrees is obtained. The energy spread can be calibrated by sweeping the RF buncher from 0 to 360° or by scanning the e-gun voltage. Given the effective voltage of the buncher, the energy spread of the beam at 1:DB1 can be obtained by comparing the maximum horizontal spread at the bunching phase (0°) with the beam position at the accelerating phase (90°).

Since energy couples to x and time couples to y, the final image gives a representation of the longitudinal emittance. This is depicted in figure 6, where the RF deflector is on at constant power in the first three images and the indicated buncher power is increased to rotate the longitudinal phase space. For these images the focusing solenoid was on and the image is corrected for the rotated x-y frame. As expected from the Liouville theorem, longitudinally compressing the beam will inherently increase the bunch energy spread. Note that with the RF buncher and deflector off, the beam spot is much smaller than the perturbed images, indicating that the sampled longitudinal emittance is not significantly affected by the transverse emittance.

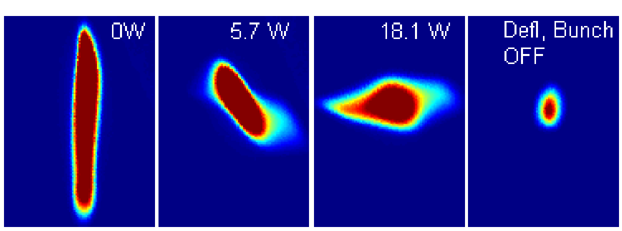

Figure 6: Rotation of the beam with the deflector on and the buncher power varied.

An alternative analysis method to determine the bunch length uses linear time invariant theory. For low space charge, the beam optics in the analyzing leg and the RF deflector can be considered a linear system and the maximum centroid deflection and maximum particle deflection over all arrival phases is time invariant. Such a system can be entirely characterized by its impulse response (i.e. the effect of the deflector on a single electron), which is well known. The output of the system will be the convolution of the input beam distribution with the impulse response function. For a uniform beam distribution of length Θ, measured in degrees RF, the centroid deflection over the maximum deflection is thus given by equation 2.

$$\frac{\Delta\bar{y}\,(\alpha)}{\Delta y_{max}} = (f * \Delta y_{\text{impulse}})(\alpha) \tag{2}$$

$$= \int_{-\infty}^{\infty} f\,(t)\,g\,(\alpha - t)\,dt \tag{3}$$

$$= \int_{-\infty}^{\infty} \text{Rect}\left(\frac{t-\theta/2}{\theta}\right)\sin(\alpha - t)\,dt \tag{4}$$

$$= \frac{\sin(\alpha) - \sin(\alpha - \theta)}{\theta} \tag{5}$$

Using this method, the bunch length can be determined by comparing the ratio of the maximum centroid deflection over the maximum particle deflection to theoretical predictions. Figure 7 shows an example of the maximum particle deflection as a function of phase offset for two different tests, highlighting the effect of bunch length in smoothing out the sinusoidal dependence. The ratio between centroid deflection and maximum particle deflection for the shorter and longer bunches is 0.9 and 0.6, respectively, corresponding to a 60° and 180° bunch length.

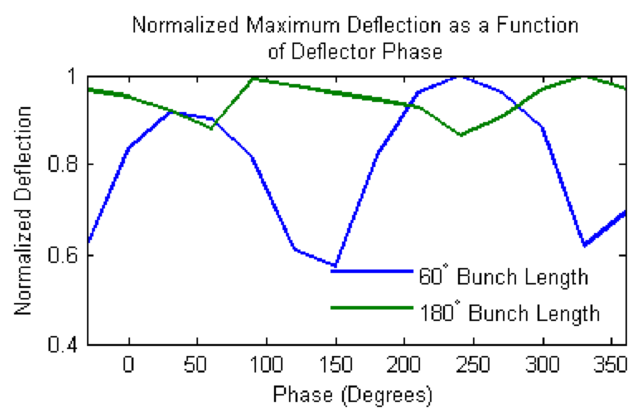

Figure 7: Maximum particle deflection as a function of RF phase for a short bunch (blue) and longer bunch (green). The phase is relative to the E-gun RF.

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[1] S.Belomestnykh et al., "Deflecting Cavity for Beam Diagnostics in ERL Injector," Proceedings of PAC'07, Alberquerque, 2007.

[2] Laxdal, R et al., "TRIUMF/VECC e-LINAC Injector Beam Test," Proceedings of LINCAC2012, Tel-Aviv, 2012.

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