Bunch Shape Measurements Using Fast Faraday Cups and an Oscilloscope Operated by LabVIEW Over Ethernet

W.R. Rawnsley, R.E. Laxdal, L. Root and G.H. Mackenzie

TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada, V6T 2A3

Abstract. A LabVIEW program running on a Sun SPARCstation 5 controls a Tektronix TDS820 6 GHz sampling oscilloscope via an Ethernet to GPIB adapter. A PC based X Window terminal continuously displays the trace, refreshed at 7 Hz. Functions such as gain, time base and application specific controls are selected by menus, buttons and dialog boxes. We have used the system to observe signals from fast (>1 GHz) Faraday cups (FFC) in the radio frequency quadrupole (RFQ) section of our Radioactive Beam Facility (ISAC). The setup utilizes the accelerator control display terminals while allowing the oscilloscope to be closer to the FFC's. ISAC uses the RFQ to accelerate singly charged ions to 0.15 MeV/u where they are stripped prior to acceleration in a drift tube linac (DTL). The time structure of the beam at the RFQ entrance was measured on a FFC placed 4 m downstream of the RFQ pre-buncher. Additional 50 Ω coaxial cone FFC's were installed downstream of the RFQ near the RFQ exit, just ahead of the stripping foil and at a double focus following the charge selection slit. The last FFC shows the increase in the mean drift time and broadening associated with the increase in energy loss and straggling caused by foil thickening under ion bombardment. Although the phase broadening cannot be corrected, the increase in the mean drift time can be corrected by changing the bias voltage on the stripper foil and thus keeping the ions in phase with the rebuncher rf.

INTRODUCTION

A radioactive ion beam facility is now under construction at TRIUMF[1]. As shown in Fig. 1, part of this facility is now complete and is being tested using stable ions from an off-line ion source. The 35 MHz cw RFQ accelerates singly charged ions from the source with q/A > 1/30 from 2 keV/u to 150 keV/u. Following the RFQ, the beam is stripped and the selected charge state is directed to a 105 MHz cw DTL[2] which will accelerate an ion beam with 1/2 > q/A > 1/6 to an energy between 0.15 and 1.5 MeV/u. The final beam will be delivered to various experimental areas.

A pre-buncher bunches the dc beam into the longitudinal acceptance of the RFQ. Although it is not yet operational, space has been left in the beam line upstream of the stripping foil for a bunch rotator which will eventually be used to provide a longitudinal waist at the foil. The beam will be rebunched ahead of each of the five DTL tanks. To facilitate measuring the bunch shape through its many transitions, we plan to use fast Faraday cups (discussed here) and particle counting devices. The bunch width will vary from 0.25 ns at the exit of the RFQ to 7.2 ns at the first rebuncher and to 0.27 ns at the exit of the last DTL tank.

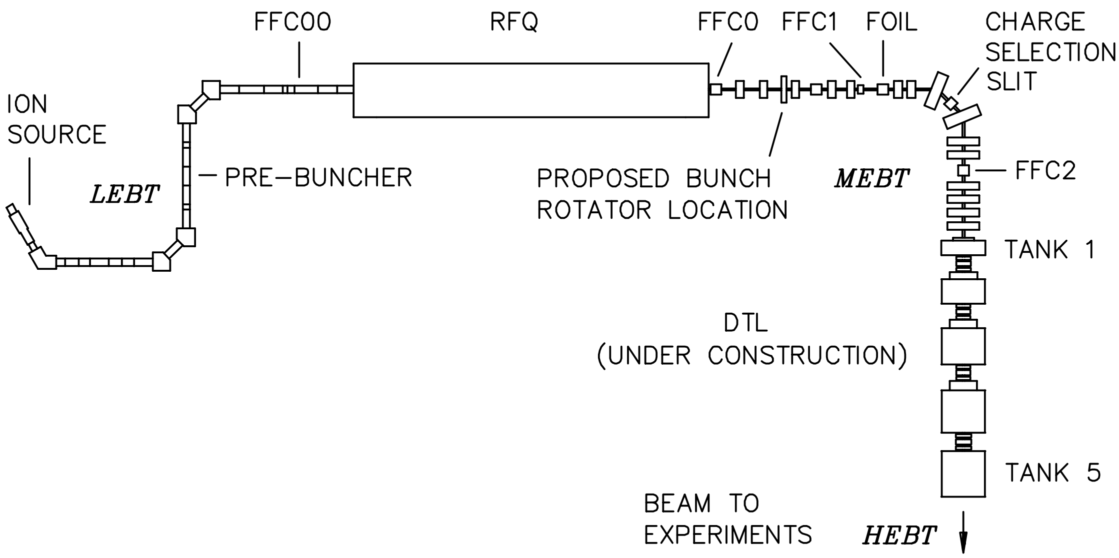


FIGURE 1. A part of the ISAC facility showing the location of the fast Faraday cups for the tests.

LABVIEW PROGRAM AND NETWORK

A LabVIEW program, inspired by work [3] at CERN, was written to provide remote control and viewing of an oscilloscope. The program allows a Tektronix TDS820 6 GHz bandwidth sampling oscilloscope located close to the beamline to be operated from a distant console. This minimizes the cost of the 3/8 in. Cable Systems foam Wellflex cable used for signal transmission and reduces signal dispersion. The oscilloscope is triggered by an 11.67 MHz sine wave from the rf control system. Fig. 2 shows the setup.

The oscilloscope's GPIB port is connected to the ISAC Ethernet using a National Instruments GPIB-ENET adapter. The adapter is assigned an Internet address that is stored in its non-volatile memory. A remotely located Sun SPARCstation 5 running Solaris 3 hosts LabVIEW 5.1. LabVIEW uses the Virtual Instrument Software Architecture (VISA) standard for communication over external buses while TCP/IP and UDP packets are generated by the adapter driver. The Internet address of the GPIB-ENET adapter is stored in the driver as a Uniform Resource Locator (URL) which is converted to a numeric address via a domain name server. The VISA session to the adapter is opened by naming the adapter (up to 8 may be controlled by a Sun) and passing the GPIB address of the oscilloscope to it (up to 14 devices may be connected to each adapter). The software is very robust; GPIB errors may occur due to network problems, but they merely generate an error message and the program keeps trying automatically until it recovers communication. The program multitasks well and requires only a few percent of the Sun's CPU time.

The Virtual Instrument (.vi) program creates an X Window display which can be viewed on remote terminals as shown in Fig. 3. We usually use the PC's that control the ISAC facility.

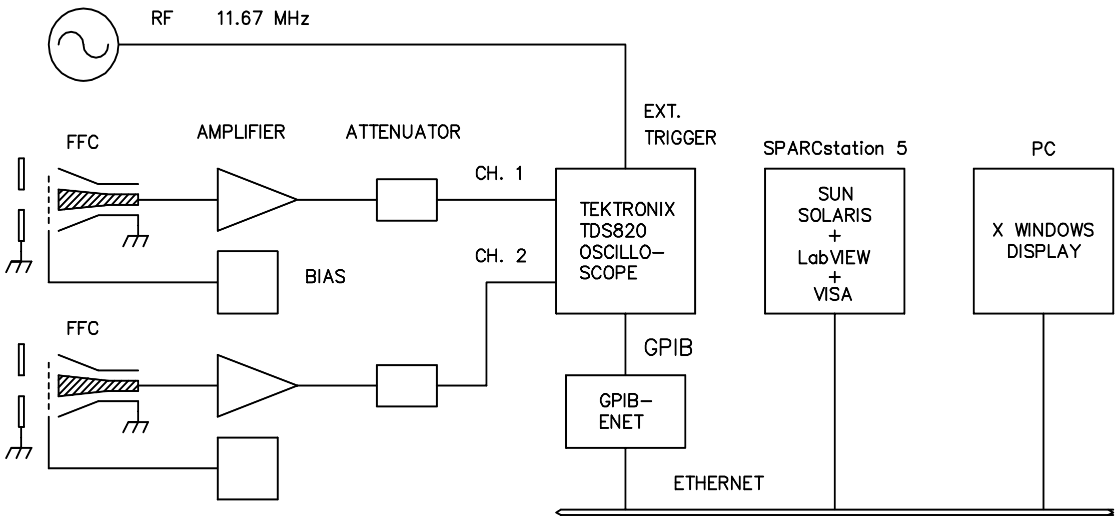


FIGURE 2. The data collection scheme takes advantage of Ethernet for flexibility and ease of installation.

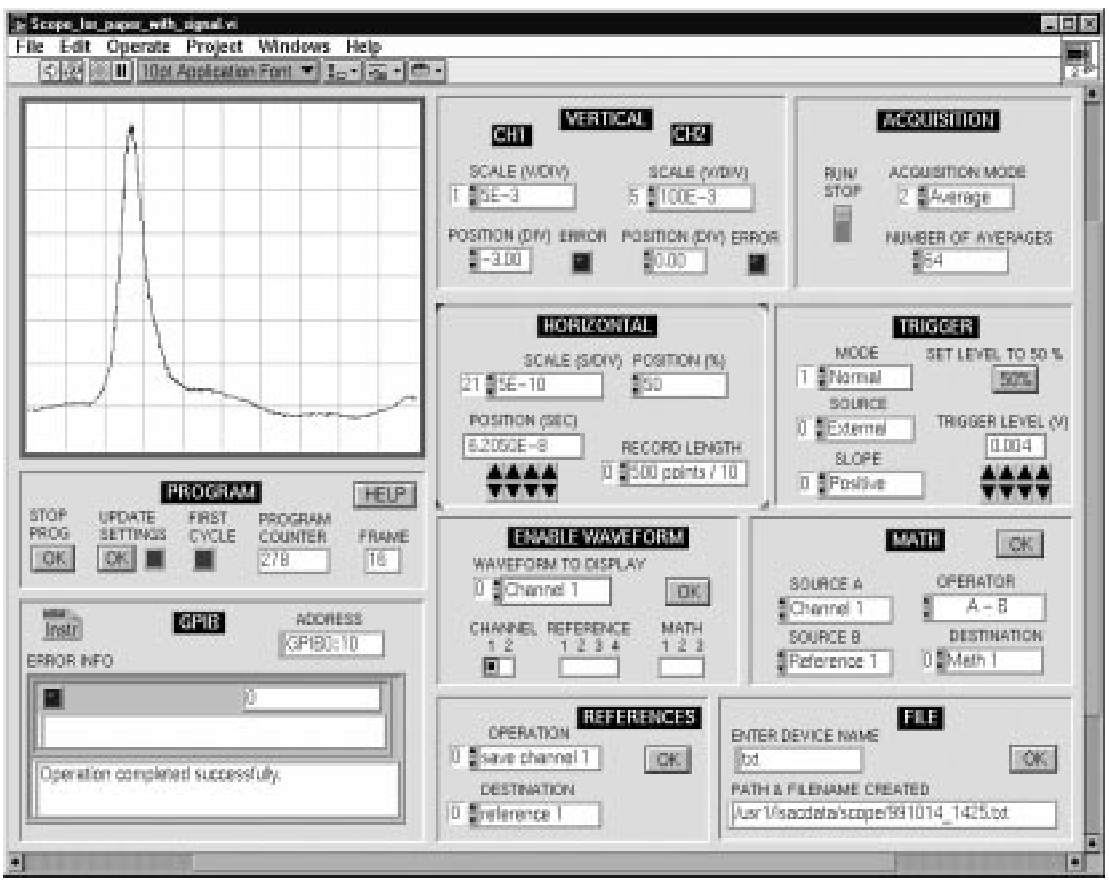
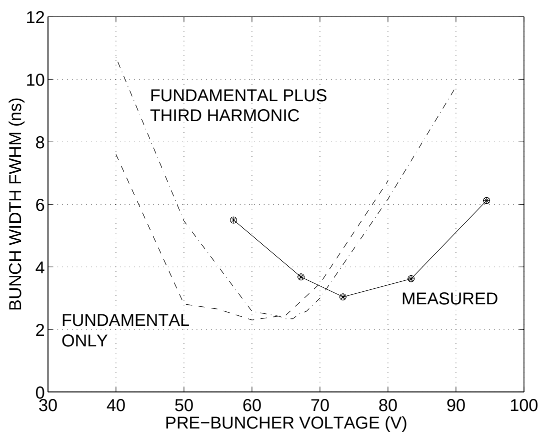


FIGURE 3. The operator interface mimics an oscilloscope front panel but is mouse and keyboard driven.



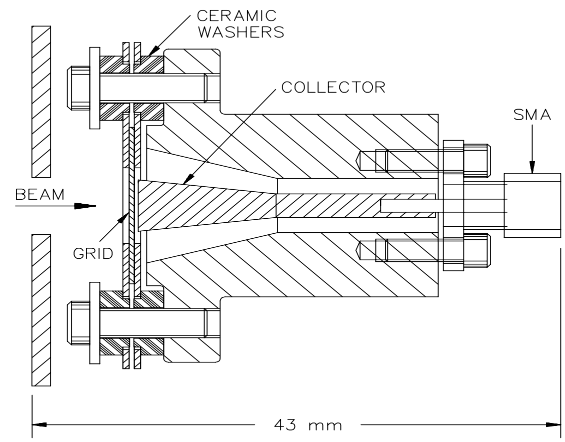


FIGURE 4A AND B. A) The FWHM width of the bunch for a fundamental only pre-buncher voltage compared with two simulations. B) A cross-section view of the TRIUMF FFC.

The operator can adjust the usual oscilloscope functions such as gain and time base using buttons and pop up menus. Variables with a wide dynamic range such as the horizontal position (delay) can be typed in directly or jogged using four sets of coarse to fine tune buttons. It has often been found to be more convenient to use these controls than the multi-layered menus on the oscilloscope's front panel. The data can be saved as ASCII files on the host machine using file names created from the date and time with the device type as the extension. The display update rate is about 7 Hz for 500 points. The rate is limited about equally by the speed of the network and the speed of the back end processor in the TDS820. We commonly use averaging in our measurements, but this process is performed in the oscilloscope and does not affect the display update rate. Two anomalies were found with the TDS820. It can take up to 10 s for it to remotely switch between channels, limiting its flexibility, and it is much faster to send only the trace information for each update, rather than including the header information each time.

The program runs in a continuous loop. It checks for any operator inputs and sends the appropriate commands to the oscilloscope. It then gets new trace data and updates the display. National Instruments provides easy to use routines for performing basic oscilloscope functions for single measurements. For continuous, interactive control, however, some of the routines must be rewritten to allow access at a slightly lower level and an overall system must be built up. This is facilitated by the graphical programming language, which can be learned very quickly. Fortunately the language automatically tends to the details of the GPIB bus and network protocols which would otherwise be a major part of the effort. Although developed on a PC running Microsoft Windows 98 the .vi file ran immediately when transferred to the Sun with only minor changes to the screen fonts required.

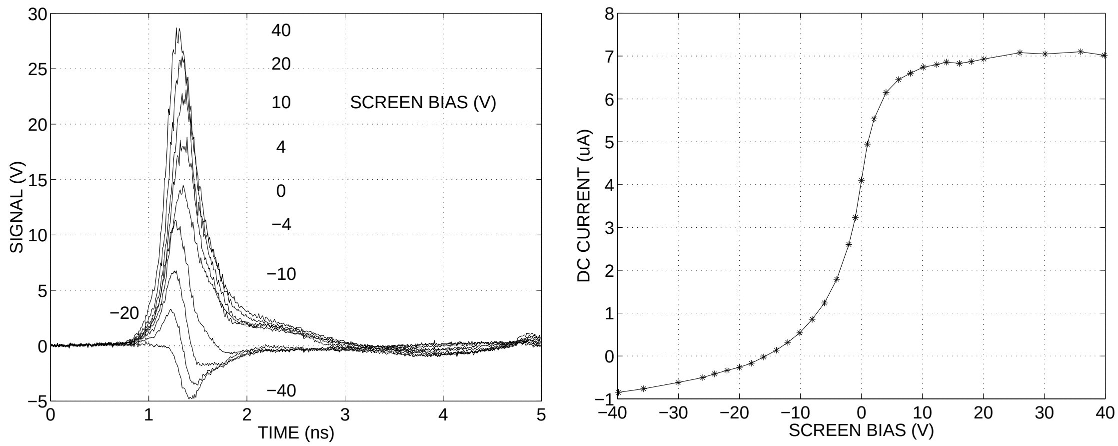


FIGURE 5A AND B. Positive bias on the screen attracts secondary electrons emitted from the collector and produces both larger ac and dc signals than a negative bias.

FAST FARADAY CUPS

The first FFC that we used was donated by M. Poggi of the INFN-LNL laboratory[4]. It is a coaxial cone with a grounded ~1 mm copper grid 0.4 mm in front of a 5 mm diameter collector. The grid is required to shield the cup from the electric field that precedes the slow moving ions. A 5 mm collimator was placed ~5 cm in front of the cup and the device was placed ahead of the RFQ at FFC00 to test the performance of the RFQ pre-buncher. The RFQ operates at 35 MHz while the wide band pre-buncher operates at a fundamental frequency of 11.67 MHz, to populate one in three rf buckets. The pre-buncher RF system can control the amplitude and phase of the first four harmonics of 11.67 MHz. Fig. 4A shows the FWHM of the bunch shape when only the fundamental was applied. 3.4 μA of 29 keV $^{14}N^{+}$ ions passed through the pre-buncher and then through a 4.0 m drift space to FFC00. As the amplitude was increased, a minimum width of 3.0 ns was measured at V_P ~75 V, where V_P is the amplitude of the fundamental component of the pre-buncher voltage. Unfortunately, the pre-buncher rf amplifier distorts the wave shape, adding about 10 % third harmonic. Two simulations were made, first using a sine wave voltage and then using an approximation of the distorted pre-buncher voltage. The simulations took into account the emittance of the beam by calculating the paths of the off axis particles at the pre-buncher and the time variation of the gap voltage as the particles transverse it but ignored space charge effects, which become significant for currents above 1 μA. The minimum bunch width of the simulations, 2.3 ns, is a little less than that measured. The comparison indicates that a correction factor of ~20 % should be applied to the measured voltage to obtain the effective pre-buncher voltage.

A subsequent TRIUMF FFC design, shown in Fig. 4B, uses a molybdenum screen supported by ceramic insulators, which transmits 67 % of the incident beam. The cup was placed ~36 cm after the last RFQ element (location FFC0 in Fig. 1) and 420 nA of $^{28}N_2^{+}$ ions were accelerated. The screen is 0.3 mm from the collector surface and coupled to ground by a 0.01 μFd capacitor in addition to the distributed capacitance of

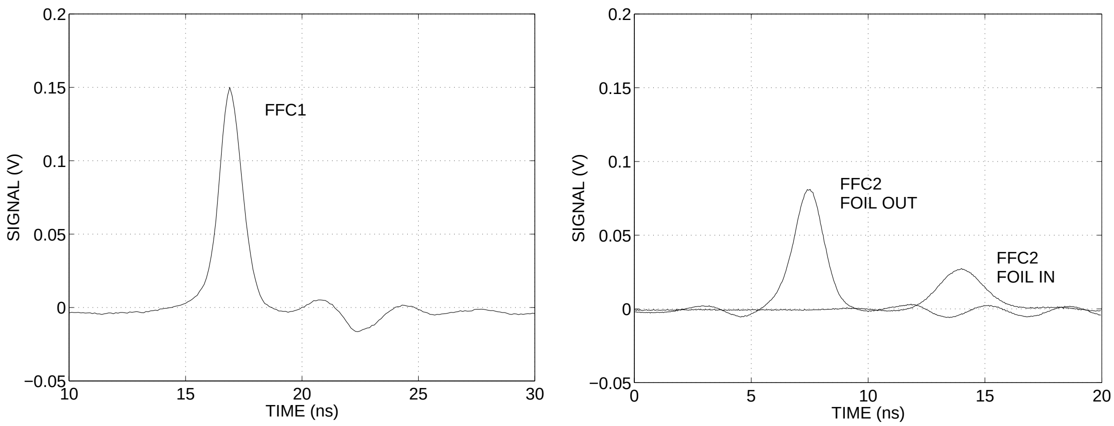


FIGURE 6A AND B. FFC signals for 210 nA $^{4}He^{+}$ ahead of the foil at FFC1 and downstream at FFC2 with foil in and foil out.

the ceramic washers. The FFC output was connected directly to the oscilloscope and a bias on the screen was varied as shown in Fig. 5A. Typically 64 to 256 averages were needed to obtain a clear bunch shape. Background subtraction was used to remove some small 35 MHz rf pickup from the RFQ. The 150 keV/u ions have a speed of 5.36 mm/ns and the time of flight (TOF) of the ions from the grid to collector imply an ultimate time resolution of 0.1 ns. The electrical signal is made up of positive ions in the beam plus secondary electrons from the edge of the collimator and grid wires and secondary electrons leaving the surface of the collector. They contribute to both the amplitude and the width of the electrical signal. The energy of the electrons is low, < 20 eV and the relative proportions of the electric components can be varied by biasing the grid [5]. The FWHM was the least with +40 V bias and the signal amplitude the greatest. The FWHM was about 0.1 ns greater with 0 and -40 V bias and the signal amplitude was smaller by a factor of 2 and 6, respectively. The smallest FWHM measured was 0.35 ns (4.4° at 35 MHz) compared to a Monte Carlo simulation which yielded 0.25 ns. A tail in the signal at the 10 % level follows the peak and lasts about 1 ns. It may be due to discontinuities in the signal transmission path. A Keithley meter was used to measure the dc current from the collector and it confirmed that +40 V was sufficient to reach a plateau region, Fig. 5B. The plateau current of 7 μA exceeds the true $^{28}N_2^{+}$ current of 0.42 μA due to the effects mentioned above. The Teflon insulation of the SMA connector limits the power dissipation of the FFC to 5 W. It is planned to substitute a ceramic SMA vacuum feedthru.

POST-STRIPPING FOIL MEASUREMENTS

The FFC's can be used to measure changes in longitudinal emittance caused by the stripping foil, Fig. 6A and B. TRIUMF style FFC's were placed at the locations FFC1, ~25 cm ahead of the foil, and at FFC2, 3.3 m after the foil. The stripping foil is 4.16 m after the exit of the RFQ and the energy spread leaving the RFQ is about 0.1 to 0.2 %. There is no phase focussing at the moment so the time width grows as the beam travels down the MEBT. Phillips Model 774 amplifiers with a gain of 100 were used, although their bandwidth is only 2.2 GHz. 6 dB attenuators were placed at the

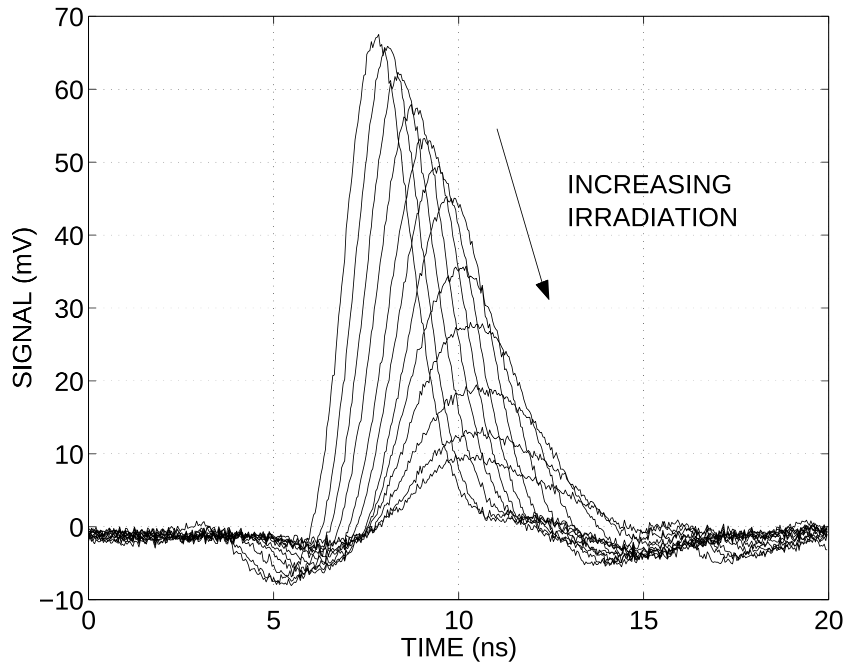


FIGURE 7. The bunch shape measured every 5 minutes as the foil degraded.

oscilloscope inputs to protect the sampling circuits, which are very sensitive to static discharge. 210 nA of 0.15 MeV/u $^{4}He^{+}$ was delivered to the 5 μg/cm^2 carbon foil location. The bunch shape of the unstripped beam was measured at FFC2 and then the foil was inserted, the bending magnets, Fig. 1, were readjusted slightly and the bunch shape of the singly charged ion component measured. A 6.5 ns (1.06 %) increase in the TOF from the foil to FFC2 was measured implying a reduction in energy of 12.7 keV. This is in agreement with a calculation using the program SRIM [6] assuming 5 μg/cm^2 of carbon plus 0.75 μg/cm^2 of water impregnated in the of the foil. The time width, and hence momentum width, of the beam increased ~35 %. Relative currents were measured by calculating the areas of the peaks. Inserting the stripper reduced the beam current by a factor of 0.43, as higher charge states were lost on the charge selection slit. This agrees well with the theoretical value of 0.44.

It is well known that the thickness of the irradiated area changes under bombardment and a foil that starts with a uniform thickness becomes non-uniform [7]. The change in energy can be compensated by adjusting the bias voltage applied to the foil ladder. However, the increase in longitudinal emittance is not easily compensated and the time to exceed some acceptable value may be shorter than the rupture time of the foil, thus determining its useful lifetime. Foil aging was investigated by accelerating 280 nA of $^{20}Ne^{+}$ ions and stripping them to the +5 charge state. The bunch shape at FFC2 was measured every 5 minutes. Fig. 7 displays a steady loss in mean energy, an increase in energy spread due to straggling and a reduction in beam transmission as the foil thickened. It shows that the FFC has sufficient resolution to be a useful tool for operators to monitor foil conditions periodically. The increase in the TOF of 2.5 ns after 40 minutes implies a reduction in energy of 24.4 keV, equivalent to a foil thickening of 3.0 $\mu g/cm^2$.

If we place a positive bias on the stripping foil and increase the voltage as the foil ages, the transit time increase caused by foil thickening can be eliminated, thus avoiding the eventual problem of having to make changes over time to the rf phase of the DTL. To test this procedure a bias from –10 kV to +10 kV was applied to the foil and $^{14}N^{+}$ was stripped to q = +4. The variation in the TOF from the foil to FFC2 was measured as 0.32 ns/kV although 0.44 ns/kV was expected. Similarly, $^{4}He^{+}$ stripped to q = +2 yielded 0.375 ns/kV rather than 0.513 ns/kV. The source of these errors remains unknown.

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