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# ESSENTIAL INSTRUMENTATION FOR CHARACTERIZATION OF ERL BEAMS*

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## *Abstract*

The typical requirement of Energy Recovery Linacs to produce beams with high repetition rate and high bunch charge presents unique demands on beam diagnostics. ERLs being quite sensitive to time of flight effects necessitate the use of beam arrival time monitors along with typical position detection. Being subjected to a plethora of dynamic effects, both longitudinal and transverse phase space monitoring of the beam becomes quite important. Additionally, beam halo plays an important role determining the overall transmission. Consequently, we also need to characterize halo both directly using sophisticated beam viewers and indirectly using radiation monitors. In this talk, I will describe the instrumentation essential to ERL operation using the Cornell-BNL ERL Test Accelerator (CBETA) as a pertinent example.

## INTRODUCTION

The unique diagnostic requirements for beams produced in Energy Recovery Linacs (ERLs) stem from the hybrid nature of these accelerators which combine aspects of both Linacs and storage rings. Just like their Linac counterparts, ERLs produce very bright beams with typical normalized transverse emittance of a few microns. On the other hand, the requirements on longitudinal distribution of the beam depends on particular applications. A survey of beam parameters [1] of different ERL projects around the world reveals bunch lengths from less than a pico-second for light sources, up to 50 ps for the Coherent electron Cooler proposed for eRHIC. Just like storage rings, ERLs are CW high current machines with large beam power. However, beam is continuously produced in ERLs while rings can only hold a finite amount of charge inside. This difference is very important in the context of machine protection. Consequently, the list of diagnostics essential to ERL beam operations must include monitoring of all these aspects.

Apart from the distinguishing features of the beams, ERLs are sensitive to time of flight errors and losses. The time of flight of the beam in the return loop needs to be within the target value with narrow tolerances in order to ensure correct arrival phase in the accelerating cavities. This in turn establishes correct beam energies and zero average beam loading [2], which is crucial for sustaining high currents. In this way, ERLs are operationally time of flight spectrometers. [3] Further, ERLs are designed for high average beam power up to mega-watts, so even modest losses can result in large radiation and thermal load on machine components. Consequently halo characterization and bunch arrival time measurements are crucial for high current operations along with the usual measurement of the core and the transverse position of the beam.

The Cornell-BNL ERL Test Accelerator (CBETA) [4] is a 4-turn superconducting ERL which has been constructed under the collaboration of Cornell University and Brookhaven National Laboratories and is currently being commissioned. With a target injection current of 40 mA and the top energy of 150 MeV, the diagnostics used in this accelerator serves as a representative example of essential instrumentation crucial to ERL operation. In the next section, we describe how we measure the beam centroid in CBETA. Then we explain various methods of observing the phase space distribution of the core of the beam. After this, we list instrumentation to detect beam halo and loss, including the equipment protection system. Finally we describe other miscellaneous diagnostics.

## BEAM CENTROID

Beam Position Monitors (BPMs) detect the position of the centroid of the bunch both in space and time. In terms of hardware, BPMs can be broadband devices such as button BPMs and striplines such as the ones used in CBETA, or they may work as resonant cavities which are narrowband. In the case of broadband monitors, the image charges induced by the bunches are electrically coupled to pickups and the relative amplitudes and phases of the detected impulses can be used to measure beam position. On the other hand cavity BPMs work by measuring the amplitudes and phases of specific resonant modes excited by the beam and can be used for very precise measurements. [5] ERLs pose an additional requirement on BPMs to be able to detect multiple beams at the same time, which is especially true in CBETA which has a Non Scaling Fixed Field Alternating (NS FFA) [6] return loop hosting 7 beams at the same time.

We use both time and frequency domain techniques for signal processing on broadband BPMs in CBETA. The time domain technique first uses a custom low pass filter with a cut off frequency at 800 MHz to broaden and smooth the incoming wideband signal from the buttons. Then after a programmable gain, we digitize the signal using a 400 MSPS ADC, after which a FPGA processes the data. We acquire

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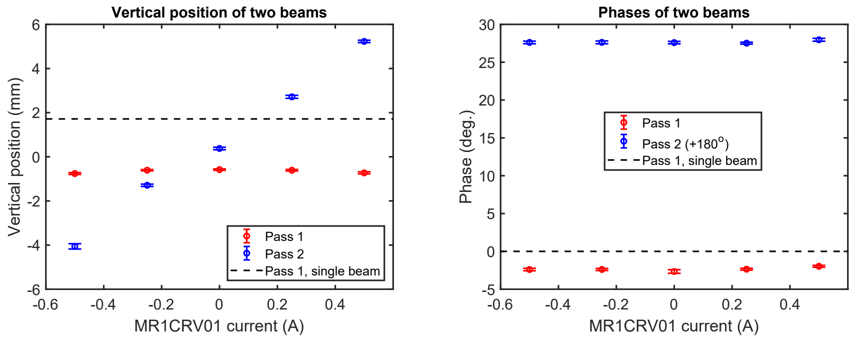

Figure 1: First tests on a dual frequency BPM just before the main linac in CBETA. The plots show the vertical position (left) and phase of the beam (right) as a function of corrector magnet setting in the recombiner line. The red points represent the injected beam going through the merger unaffected by the vertical corrector while the blue points represent the recirculated beam about to enter the main linac. The dashed lines are the baseline measurements with only the injected beam in the pipe.

the position information of separate beams by synchronizing on to the arrival times of different energy bunches, the details of which are documented elsewhere. [7] We obtain a typical transverse measurement jitter of 0.1 mm using 5 pC bunches with a 20 Hz repetition rate, while bunch arrival times can't be measured using this system.

The frequency domain technique is used to both measure position and arrival time of both accelerating and decelerating bunches in the splitter/recombiner and merger sections of CBETA. The button signals are split into two parts and processed through bandpass filters of 1.3 GHz and 2.6 GHz which are the CBETA RF frequency and it's second harmonic respectively. These are then mixed down to intermediate frequency signals which are digitized so that we can obtain their in-phase (I) and quadrature (Q) components with respect to the RF clock. We are going to document the details of this technique in a future paper. The results from initial testing are depicted in Fig. 1. The single shot measurement jitter of this system is 0.3 mm and 0.1° with one train of 10-20 5 pC bunches.

## PHASE SPACE

The phase space distribution of beams must meet specifications set by particular applications. Apart from the use of conventional viewscreens which help us measure the transverse distribution of charge at different places in the accelerator, we also need instrumentation dedicated to measuring transverse and longitudinal phase space. At CBETA, we use a multi-slit system [8], with scanning coils and a Faraday cup in a separate diagnostic line to measure the transverse emittance and twiss parameters of the injected beam as it enters the main linac. Figure 2 shows the measured transverse phase space at a bunch charge of 5 pC. Full 4D phase space measurement have been explored elsewhere [9] using tomographic techniques which rely on rotating the phase space using quadrupole magnets and measuring the resulting projections. Both these techniques need a dedicated diagnostic line and are not in-situ measurements.

The design of the longitudinal phase space of ERL beams depend on particular applications. On one hand, light sources require very short bunches while electron coolers need very long bunches up to 50 ps with small energy spread of $10^{-4}$. Applying a time dependent transverse kick using deflector cavities placed in dedicated diagnostic lines is a widely used technique. At CBETA, we use a pulsed copper cavity [10] in conjunction with slits and a Faraday cup to map the longitudinal distribution of charge as shown in Fig. 3. Other groups have demonstrated measurement of slice emittance along the longitudinal position of the bunch using tomographic projection in conjunction with deflector cavities. [11] Coherent Transition Radiation (CTR) is yet another method of measuring the longitudinal distribution, where the beam goes through a metal foil and the radiation is measured using an interferometer. [12] These are all destructive methods and we can only use them in special low current diagnostic modes of the machine. Non-destructive methods of measuring the longitudinal distribution include interferometric techniques on synchrotron radiation [13] and electro-optic modulation of laser pulses using the electric field generated by the bunch. [14]

## HALO AND LOSSES

The beam halo plays an important role in operation of ERLs. While characterizing the charge distribution in the core of the beam is important for various applications, the halo determines how much unwanted radiation the machine produces which in turn constrains the beam current. Halo measurement requires devices capable of high dynamic range, typically more than $10^6$. At CBETA we have used conventional BeO viewscreens to measure transverse halo of the injected beam. We boosted the dynamic range of measurement by averaging multiple frames and acquiring the averaged frames at multiple exposure times. Then we weighted each averaged frame with the inverse of the exposure time and subtracted a background image with the beam turned off. The result of this process is shown in Fig. 4. To rule out effects of lens flare, reflections and spurious light we scanned an upstream quadrupole magnet to verify that the halo also changes shape along with the core of the beam. Extensions of this technique include using Charge Injection

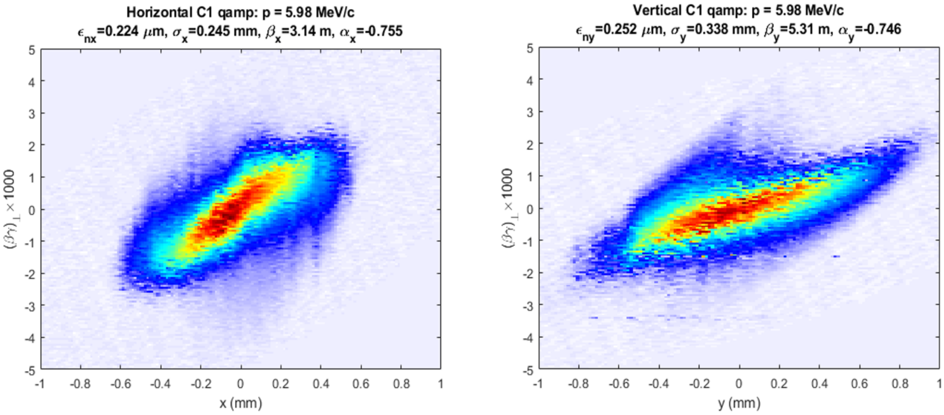

Figure 2: Measured transverse phase space of the injected beam in CBETA with a 5 pC bunch charge.

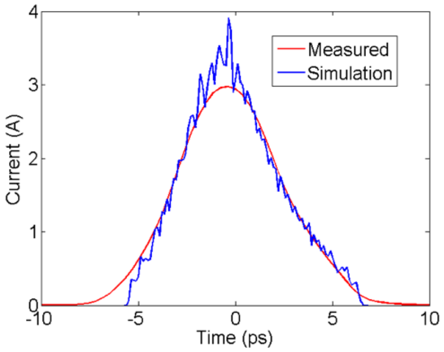

Figure 3: Longitudinal charge distribution of a 20 pC test bunch at the CBETA injector.

Device (CID) cameras and selective masking of different areas of the beam spot using micro mirror arrays. [15] Besides viewscreens, wirescanners achieve high dynamic range by introducing an intercepting monitor through the beam and recording the resulting radiation. [16]

The ionizing radiation generated during ERL operations constrain the maximum sustainable beam power and is very important from a equipment protection point of view. Scraping of beam halo on the vacuum chamber generates a steady field of radiation throughout the machine. We must measure and constrain this beam loss to make sure enough energy is recovered and sensitive equipment, for example the permanent magnet return loop in CBETA is not damaged. The amount of current lost can be measured directly using beam current monitors. In CBETA, slow monitors based on CsI scintillators coupled to PiN photodiodes provide calibrated time averaged radiation dose information primarily to monitor dose to our permanent magnets. On the other hand, we use plastic scintillating fibers coupled to photo-multiplier tubes placed all around the machine to detect catastrophic beam loss and turn off the machine within 1 µs.. An exhaustive view of machine protection has been presented in a different talk at this workshop. [17]

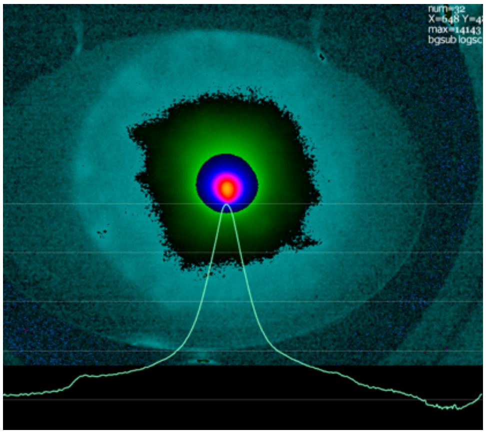

Figure 4: Halo measured at the CBETA injector using a viewscreen. The area intensity of the halo is $3 \times 10^{-4}$, while it accounts for 3% of the total charge.

## MISCELLANEOUS

Besides instrumentation dedicated to beam diagnostics, other components of the accelerator may also provide important information about the beam. At CBETA, we have used the main linac cavities to measure net transmission through our return loop. Figure 5 shows the beam loading on all six cavities of the main linac as functions of injected beam current. In the situation of perfect energy recovery, the beam loading should be independent of current, however the blue data points representing the energy recovered beam shows a small slope on all cavities. Since the beam reached the main beam stop with the nominal orbit in all cases, the residual beam loading represents net beam loss in the return loop of the machine. We measured a transmission efficiency of $99.6 \pm 0.1$ % from the fitted slopes. Cavities can also be used to detect the onset of Beam Breakup Instability (BBU) and characterize the excited Higher Order Mode (HOM) which is responsible. [18]

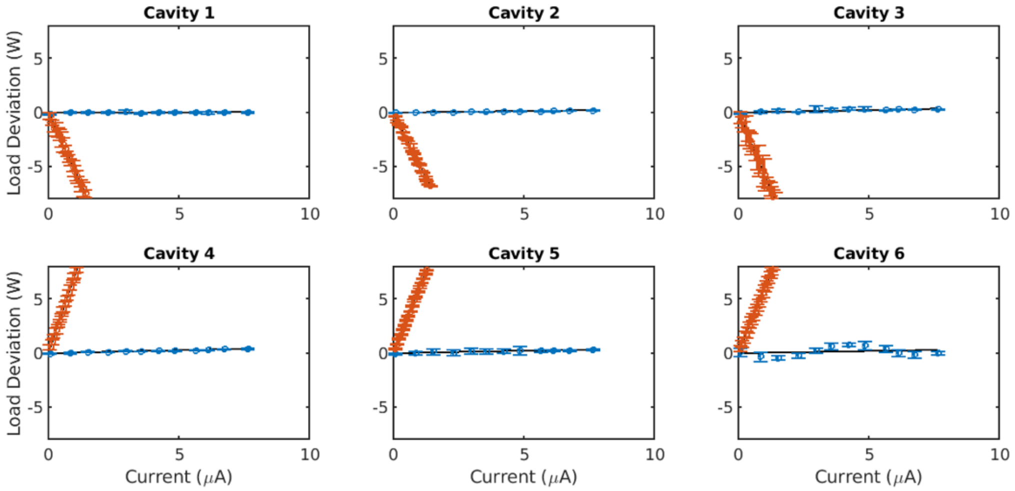

Figure 5: Beam loading as a function of injected current in the CBETA main linac cavities. The red data points represent a situation where cavities 4, 5 and 6 accelerated the beam while 1, 2 and 3 decelerated it. The blue points represent data collected during energy recovery operation.

## CONCLUSION

ERLs produce high power bright CW beams while being very sensitive to time of flight deviations and beam losses in the return loop. This necessitates an unique set of minimal diagnostics combining requirements of high power CW beams in storage rings and precise phase space measurement of linac beams. Since ERLs operate as time of flight spectrometers, we need to measure the centroid of the beam both in space and time sometimes for multiple beams in the same pipe. At CBETA, we have developed both time and frequency domain approaches to obtain this information. Besides the centroid, measurement of the transverse and longitudinal distributions is important to match with various applications. Most methods use a dedicated diagnostic line with slits, deflector cavities and associated optics and may only be used in special diagnostic modes of the machine as in CBETA. Interferometric methods which detect synchrotron radiation and electro-optic methods which detect electric field generated by bunches are non-destructive techniques for longitudinal measurement. Scraping of the beam halo with the vacuum chamber generates unwanted radiation which can be detrimental in ERLs due to the very high currents involved. Measuring halo requires a device with high dynamic range which may be achieved by controlling exposure times on viewscreens as is done for CBETA or using intercepting wire monitors. While we can use beam current monitors to directly measure current loss, radiation monitors are crucial for machine protection and are employed in CBETA to protect its permanent magnets. Finally, cavities are also important diagnostic tools capable of measuring net transmission and diagnosing BBU.

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