# CURRENT MEASUREMENT AND ASSOCIATED MACHINE PROTECTION IN THE ERL AT BNL*

T. Miller†, D.M. Gassner, J. Jamilkowski, D. Kayran, M. Minty, J. Morris, B. Sheehy
Brookhaven National Lab, Upton, NY 11973, USA

*Abstract*

The R & D Energy Recovery LINAC (ERL) at Brookhaven National Laboratory (BNL) requires accurate and precise current measurements for logging and for machine protection. In this paper we present techniques used to measure the beam charge and current during commissioning in pulsed and CW operating modes. The strategy for ramping up the total beam current is discussed, including the motivation for developing different operating modes with specific pulse structures, tailored by the constraints imposed by the operating limits of the instrumentation. The electronics packages used for integration and digitization are presented along with methods of synchronization. Finally, results of measurements made during the first beam tests are presented.

## INTRODUCTION

The ERL is operated in a wide variety of operating modes; where the beam parameters, such as pulse structure, charge, and average current, vary widely from one mode to another. This presents a challenge to accurately measure the charge and current of the beam under all conditions. The two most prevalent operating modes are the "High Charge" and "High Current" modes [1]. The operating parameters for these modes are summarized in Table 1. An "Instrumentation" mode (not shown in the table) is also used with a repetition rate of only 1 Hz and where the total charge deposited on insertion instruments is limited and protected by the machine protection system (MPS).

Table 1: Operating Modes

| **Parameter** | High Charge | High Current |
|---|---|---|
| Energy | 2.0 – 20 MeV | |
| Current | 50 mA | 500 mA |
| Charge | 0.05 – 5 nC | 0.7 nC |
| Bunch Rep. Rate | 9.38 MHz | 704 MHz |
| Bunch Length | 30 ps | 20 ps |
| Macrobunch Rep. | 5 kHz | 5 kHz |
| Macrobunch Length | 0 – 7 μs (ICT)<br>up to CW (DCCT) | |
| Train Rep. Rate | 1 Hz | |
| Train Length | 0 – 900 ms | |

† tmiller@bnl.gov

*Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. DOE

Instrumentation is required to report the beam charge and/or current while operating in these modes. Table 2 summarizes the requirements that are met by using multiple instruments and tailoring the operating modes to work within the limitations of each instrument.

Table 2: Measurement Requirements

| **Parameter** | **Current** | **Bunch Charge** |
|---|---|---|
| Range | 50 μA – 500 mA | 10 pC – 5 nC |
| Accuracy | 1 % | 5 % |
| Resolution | 0.1 %<br>(at I=500 mA) | 0.1 %<br>(at 5 nC) |

Among the dense population of instrumentation on the beam line [2], a Faraday Cup is mounted to the end of a diagnostic beam line for direct measurement of beam charge. The high-power beam dump is isolated and also used as a Faraday Cup. Nondestructive charge measurements are made by an Integrating Current Transformer (ICT), located just downstream of the gun. Measurements with the ICT are limited to beam pulses under 7 μs at a repetition rate of less than 10 kHz. For pulse trains longer than 100 μs, the average current is measured in two places by DC Current Transformers. The locations of these instruments are shown in the symbolic layout of the machine in Fig. 1.

## CURRENT MEASUREMENT

### *Faraday Cup*

The two Faraday Cups, one on the diagnostic beam line and one at the beam dump, are unbiased and directly connected to ¼-inch Heliax cables (Andrews LDF1-50) that bring the signals back to integrating electronics. A BNL designed amplifier is used with High and Low gain settings for both Pulsed & DC modes. The calibration in Pulsed mode corresponds to 9 μA/V and 90 μA/V for the High and Low gain settings respectively. The amplifier output is fed to a BNL designed 8-channel integrator with Reset and Gate functions controlled by the ERL Timing System to correspond with the beam pulse structure. The integrator's output is digitized by a VMIC3123 digitizer that is triggered at the beginning of the beam pulse train.

Preliminary commissioning of the beam with the Faraday Cup (FC) in the diagnostic beam line was made with a direct connection to an oscilloscope. The voltage signal induced by the impinging beam is slowed by capacitance in the system. This capacitance was calculated from the discharge portion of the FC response to dark current produced during a 10 ms RF pulse, as shown in Figure 2.



ISBN 978-3-95450-183-0

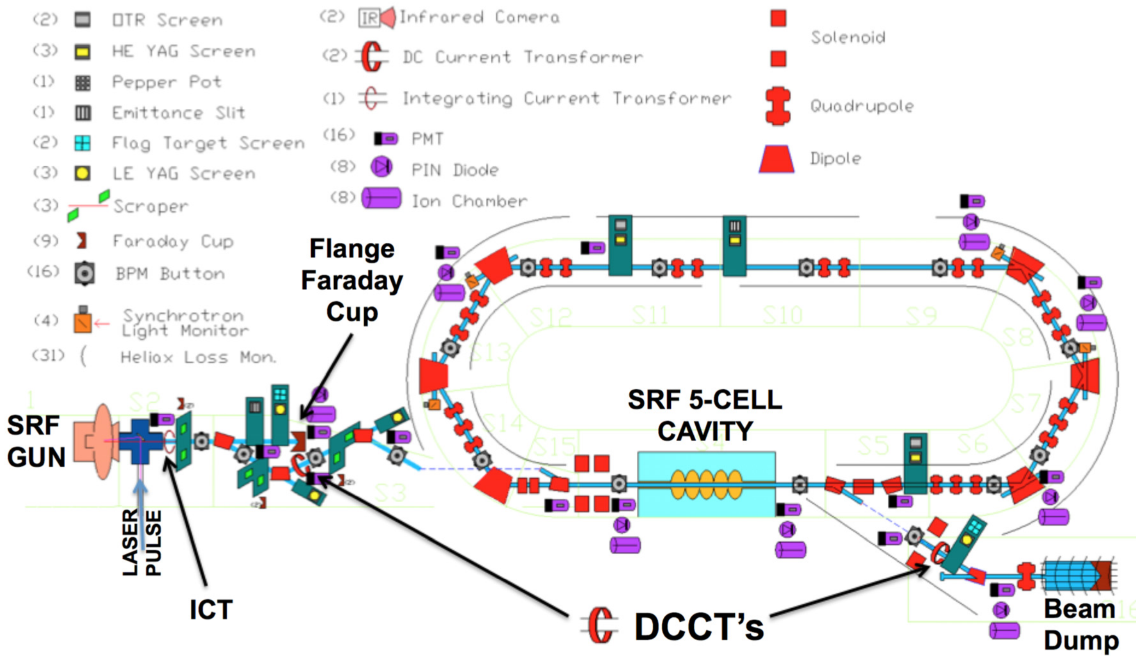


Figure 1: Symbolic layout of ERL with instrumentation.

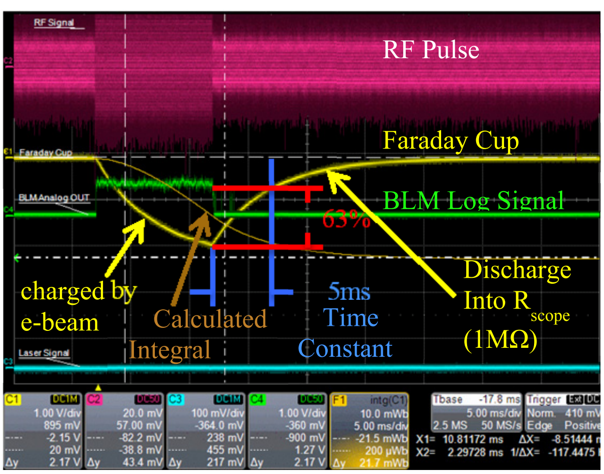


Figure 2: Faraday cup signal with pulsed beam – dark current.

The FC signal dropped by 63 % (one time constant) in 5ms as the capacitance discharged. Using equation 1 below with 1 MΩ from the scope input impedance and the measured 5 ms time constant;

$$\tau = RC \tag{1}$$

the system capacitance was found to be 5nF. Equation 2 below gives the total charge deposited by the dark current during the 10 ms pulse.

$$Q = \int I(t)dt = \frac{1}{R}\int V(t)dt\,. \tag{2}$$

Using equation 3 with equation 2 for Q, R=1 MΩ from the scope input impedance, T=10ms duration of the beam during the RF pulse, and the integrated voltage of 21.7 mV-s from the scope function;

$$\bar{I} = \frac{Q}{T} = \frac{1}{RT}\int V(t)dt \tag{3}$$

the average dark current during the RF pulse was found to be 2 μA, similar to measurements presented earlier [3]. Using the system capacitance, the charge from the photocurrent was found from Q=CΔV; where ΔV is the peak-to-peak change in voltage during the photocurrent pulse and C is the system capacitance of 5nF. This was measured in Fig. 3 to be 158 mV; giving a charge of 0.8 nC per pulse, considerably higher than measurements presented earlier [4]. Figure 3 shows three consecutive photocurrent pulses superimposed on the slow curve from

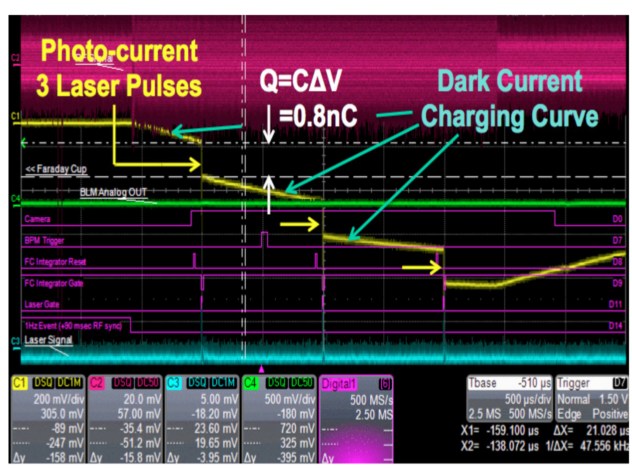


Figure 3: Faraday cup signal with photo current.

ISBN 978-3-95450-183-0

the dark current that contribute to the FC signal with each photocurrent pulse.

### *Integrating Current Transformer*

For nondestructive charge measurement of the beam, an integrating current transformer is installed just downstream of the gun. It is installed in an in-flange type 6-inch Conflat® that includes an internal uncoated ceramic break. Made by Bergoz Instrumentation [5], its part number is ICT-CF6-60.4-070-05:1-H-UHV-THERMOE with a turns ratio of 5:1. Although the target vacuum level of $5\times10^{-9}$ torr was met without the need for bake-out of the beamline, provisions for bake-out were made in the system design in the event it becomes necessary. Consequently, an internal type E thermocouple was included for temperature monitoring. This non-standard feature was developed on request for the ERL. The bake-out must be monitored as irreversible modifications to the toroid are expected to occur when the magnetic core is heated beyond 100 °C, with an immediate consequence of a loss of magnetic permeability. Experience of the manufacturer shows that while no loss is expected at 100 °C; at 168 °C, there can be as much as 50 % irreversible loss, resulting in an increase in output droop. The extent of the output droop depends on the transformer's turns ratio. With a 5:1 turns ratio, the droop is estimated to be about 6 %/µs. With a 50 % loss of permeability, the droop is expected to double to 12 %/µs.

This ICT is used in conjunction with a Beam Charge Monitor (BCM) electronics module, from Bergoz, that provides an Integrate-Reset-Hold (IHR) function. The device is triggered just before a beam pulse such that its adjustable integration window (0 – 7 µs) spans the beam pulse. Due to this limited range of integration window, only beam pulses shorter than 7µs can be measured. The BCM can be retriggered at a repetition rate of up to 10 kHz. There are 7 gain settings providing full-scale ranges of 0.8 to 40 nC. The sensitivity of the ICT + BCM-IHR is given in equation 4.

$$n/Q = \left(\frac{V_{FS}}{Q_{FS}}\right)_{BCM} * \left(\frac{n_{FS}}{V_{FS}}\right)_{Digitizer} \quad (4)$$

Thus for the most sensitive scale (40 dB gain), we find n/Q = 655 counts/nC; where the BCM full-scale output voltage $(V_{FS})_{BCM}$ is ±10V, the BCM full-scale charge $(Q_{FS})_{BCM}$ is 0.8 nC, the digitizer full-scale input voltage $(V_{FS})_{Digitizer}$ is ±10V, and the full-scale number of counts for the 16-bit digitizer $(n_{FS})_{Digitizer}$ is 65,553 counts.

As it is important for the timing of the IHR integration window to span the beam pulse (or "macrobunch" of pulses), the machine operating procedures call for a verification of the timing alignment on an oscilloscope, at the start of each operating shift, as shown in Fig. 4.

The measured beam pulse, or macrobunch shown in Fig.4, consisted of 9 photocurrent pulses at 9.38 MHz repetition rate. The total integrated charge within the 7 µs window was 1.68 nC. Thus the charge per pulse was 0.19 nC/pulse.

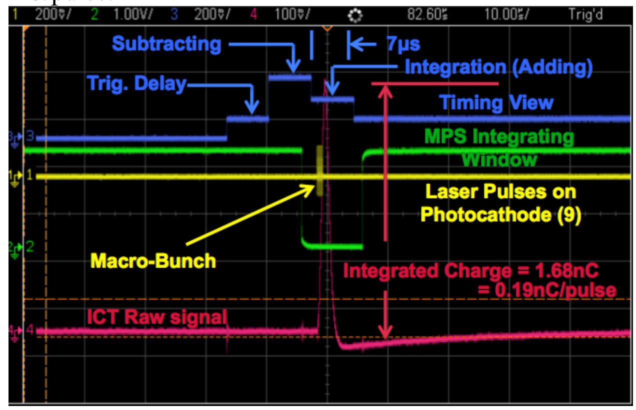


Figure 4: ICT measurement & timing signals.

### *DC Current Transformer*

For beam pulse trains longer than 100 µs, two DC current transformers (DCCT), model NPCT (New Parametric Current Transformer) made by Bergoz are installed in the Zig-Zag injection section and in the extraction beam line. Installed over an uncoated ceramic break, this device is also sensitive to bake-out temperatures over 80 °C. Therefore, a custom cooling coil was fabricated and installed between the bake-out heating blanket (over the ceramic break) and the DCCT to prevent the core from overheating. The DCCT with its matched electronics package from Bergoz has four output scales ranging from ±20 mA to ±20 A. A ±10 V analog output voltage is provided by the amplifier module delivered with the transformer. The 70 µs rise time response of the DCCT gives about 50 us of flat-top with a 100 µs long macrobunch. Only the flat-top portion of the signal is considered as valid data during the digitization process.

### *Digitization*

A VMIC3123 [6] digitizer handles macrobunch level data acquisition for the Faraday Cup and ICT signals. Sampling at 100 kHz, it is triggered at the start of a train of macrobunches and collects up to 320 ms of data. The digitizer may be upgraded once the ERL begins operating with pulse trains longer than 320 ms. The data is then processed in the VME Front End Computer (FEC) to pick out a peak value for each macrobunch. The signals are held long enough by the integrating electronics to ensure that a peak value will be captured in one of the 100 KHz samples for every macrobunch.

The VMIC3123 system (including Front End Computer software) can digitize and deliver up to 320 ms of data once per second. Configuration of the system involves setting the variable "dataArraySizeS" for the train length, "samplesPerPeakPeriodS" for the time between macro-bunches, and "peakThresholdS" for the minimum level recognized as a macrobunch peak. An upgrade to the ERL Timing Control Manager is planned that will update these values as the ERL timing changes.



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An algorithm processes the Faraday Cup data each second to mask transients in the integrator's output caused by timing triggers that interfere with the peak-finding algorithm. As proper suppression of these transients requires a redesign of the integrator, a mask signal is generated, coincident with the offending integrator-timing signal, and is digitized at 100 KHz along with the integrator's output signal. Only data outside of the mask signal is used in the peak-finding algorithm. The filtered peak-finding software is currently being run on a Linux system using raw data signals delivered from the VMIC3123 in the FEC.

The analog output of the DCCT's NPCT electronics is digitized at 625 kHz by a National Instruments PXI-6289 data acquisition module. Work is underway to implement a triggered acquisition of the DCCT's measurement of the beam current of macrobunches longer than 100 µs. The system will average samples taken over the flat-top portion of the macrobunch measurement. In order to measure only the signal's flat-top, the digitizer will begin


Figure 5: DCCT response to 200 µs long macrobunch; DCCT signal on yellow trace, pulse train on blue trace.

sampling the DCCT signal at the start of a pulse train (at 1 Hz) and also sample a gate pulse that defines the useable portion of the signal. Only the DCCT data that falls within the windows defined by the gate signal is averaged to report the current at the end of the train. The gate signal is delayed to account for the 70 µs of rise time and ends at the end of the macrobunch. Figure 5 shows the response of the DCCT (Ch1) to a 200 µs train of pulses (Ch3) at 9.32 MHz.

## TIMING & PULSE STRUCTURE

In order to measure the charge and/or current proficiently in pulsed mode, the beam pulse structure is tailored by the limiting parameters of the ICT; which can measure only a 7 µs window at a repetition rate of up to 10 kHz. First beam tests were made with a single ~30 ps laser pulse on the photocathode at a 1 Hz repetition rate. Ramping up average current consists of additional pulses being grouped together into a macropulse. The repetition rate of the pulses within the macropulse is driven by the laser clock frequency at 9.38 MHz. The pulse count per macrobunch can be increased up to 65 pulses to fill the 7 µs maximum window of the ICT. However, to ensure that the macrobunch fits reliably within the ICT integration window, a maximum of 50 pulses is chosen. A maximum charge of 550 pC/pulse was demonstrated from the 703 MHz SRF Photoinjector in the most recent beam tests of June 2015 [7] yielding a maximum possible charge per 50-pulse macrobunch of 27.5 nC. Although these high charge pulses were demonstrated, early commissioning techniques utilized pulses of under 200 pC to minimize space charge effects; thereby resulting in a maximum of 10 nC per 50-pulse macrobunch.

For low power commissioning of the beam line, a technique of ramping up the current was devised, as shown in Fig. 6, that keeps a steady average current over the length of the RF pulse. Recent commissioning of the

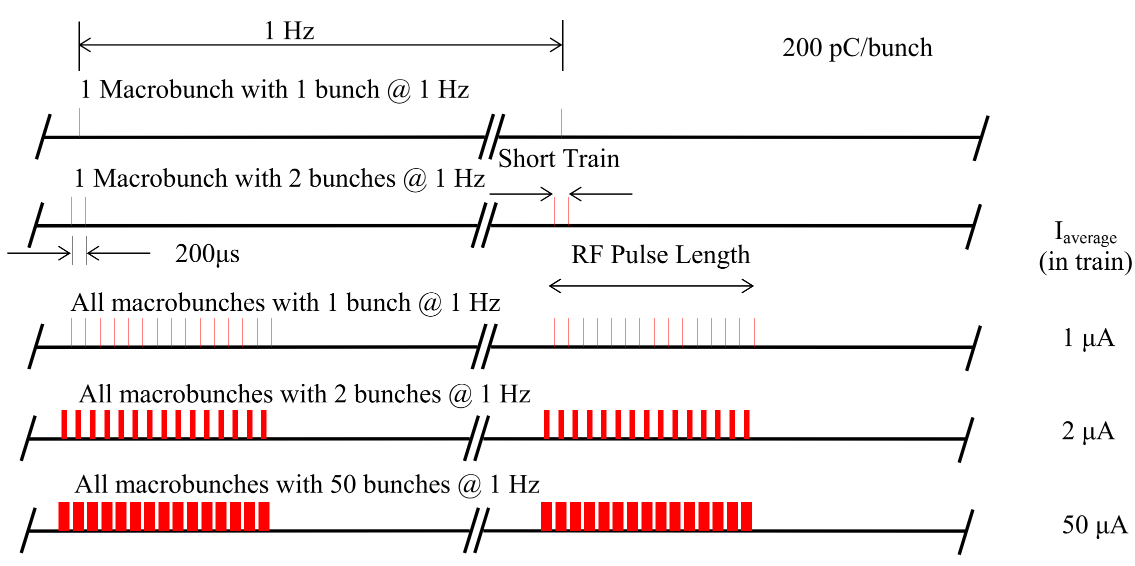


Figure 6: Pulse Train Structure for ramping up total beam current. $I_{average}$ is based on 200pC/bunch.

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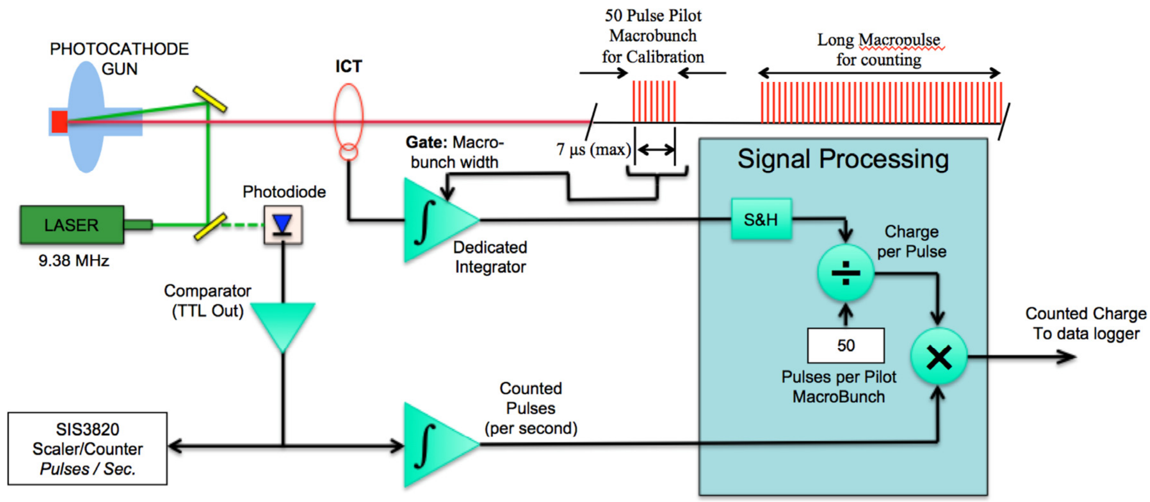


Figure 7: Pulse counting scheme with pilot pulse timing structure.

SRF gun required limiting the SRF cavity pulse to <10 ms due to vacuum excursions. The duty factor is planned to increase as the cathode is conditioned over time. To keep the average current steady, a continuous train of macro-bunches was produced for the length of the RF pulse. Although the BCM electronics are capable of 10 kHz, a dedicated integrator used to process the ICT signal for the MPS functions up to 5 kHz only. Therefore, a train of macrobunches was formed at 5 kHz. Beginning with a single 200 pC bunch in each macrobunch results in an average current of 1 µA (200 pC × 5 kHz) within the train. Further increases in current are made by adding bunches to each macrobunch in the train up to 50, resulting in an adjustable in-train current of 1 – 50 µA. The total average current then depends on the duty factor of the RF pulse.

## PULSE COUNTING

To reach high average currents, the macrobunch length will eventually have to grow beyond the limited 7 µs maximum integration window of the ICT. To extend the charge measurement to accommodate these longer macrobunches, a pulse counting technique is used to count the number of laser pulses every second.

A photodiode (Thorlabs DET 36 A, 14 ns rise time) samples the laser beam striking the first turning mirror after the laser exit. A comparator (Pulse Research Labs PRL-350 TTL, 0 mV threshold) converts the analog photodiode pulses to TTL pulses that are counted by a scaler/counter. The response time of the photodiode is long enough to trigger the comparator, but short compared to the laser repetition period of 106 ns. The scaler (SIS 3820, from Struck Innovative Systeme) is reset every second and reports the total pulses/sec counted to the Control System.

Using the pulse count to predict the total charge requires an accurate calibration of the charge per pulse. A pulse structure implementing a "pilot pulse" is proposed, as shown in Fig. 7, with long pulse trains to allow the ICT to measure a sample of the pulse train and provide a calibration.

## MACHINE PROTECTION

In addition to measuring and logging beam current, the ICT is also used to report macrobunch charge to the machine protection system (MPS) to shut down the beam in the event that measured charge levels exceed thresholds for insertable destructive instrumentation. A dedicated integrator is used to process the BCM output labeled "Signal View" (ICT signal before integration). An amplifier is used to buffer the output and add an offset adjustment to drive the integrator's input. Although the electronics is capable of 10 kHz operation, this dedicated integrator is limited to operation at 5 kHz. The charge reported by the ICT is compared to four individual thresholds for the following groups of instruments: Profile Monitor, Dipole Profile Monitor, Emittance Slit Mask, & Halo Monitors. The insertion of an instrument enables the corresponding group threshold for comparison to the measured charge. Operation in a mode called "Instrumentation Mode" will limit all macrobunch lengths to under 7 µs (optimally only 50 pulses).

Figure 7 shows a proposed scheme to sample and hold the integrated charge measured from one "Pilot Macrobunch". Although a platform on which to implement the scheme shown has not been specified, it would divide the pilot macrobunch charge by the number of bunches to arrive at a calibration coefficient (charge/bunch) that would be multiplied by the total number of counted pulses (bunches) in one second; thereby calculating the total beam charge per second, or average beam current.

## CONCLUSION

Current measurements at the BNL ERL are accomplished with three instruments, Faraday Cup (FC), Integrating Current Transformer (ICT), and DC Current



ISBN 978-3-95450-183-0

Transformer (DCCT). The FC provides destructive charge measurement at the end of the diagnostic beam line; while the ICT provides operational measurement of the beam charge, but limits the beam duty factor to < 3.15% (7 μs × 5 kHz × 90 %). A laser pulse counter provides a check of the total pulses per second and a scheme to derive total beam charge is proposed.

The beam pulse structure is tailored to fit within the timing constraints of the ICT and associated electronics. For longer pulse trains, the DCCT provides average current measurement over 1 second at two places: zig-zag injection beam line and the extraction beam line. The MPS offers protection of the insertion instruments against over exposure to beam charge with separate thresholds for four different instrument groups.

### *Future Plans*

A technique of alerting the MPS in an event that more than 50 pulses are generated per macrobunch while operating in the "Instrumentation Mode" needs to be implemented. Work is ongoing to implement a differential DCCT current measurement [8] between injection and extraction beam lines with an interface to the MPS.

## ACKNOWLEDGEMENTS

The authors acknowledge the contributions of Ilan Ben-Zvi, W. Xu and other members of the Accelerator R&D Division, Instrumentation Systems Group, Accelerator Components & Instrumentation Group especially C. Dawson, C. Degen, L. Desanto, S. Jao, the Controls Group especially P. Harvey, P. Kankiya, the Vacuum Group, the Collider Mechanical Support group especially S. Seberg, and members of the Design Room.

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ISBN 978-3-95450-183-0