BNL ENERGY RECOVERY LINAC INSTRUMENTATION*

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Abstract

The Energy Recovery Linac (ERL) project is currently under development at the Brookhaven National Laboratory. The ERL is expected to demonstrate energy recovery of high intensity beams with current up to a few hundred milliamps, while preserving the emittance of bunches with a charge of a few nC produced by a high current SRF gun. To successfully accomplish this task the machine will include beam diagnostics that will be used for accurate characterization of the three dimensional beam phase space at the injection and recirculation energies, transverse and longitudinal beam matching, orbit alignment, beam current measurement, and machine protection. This paper describes the present status of the systems that will be used to meet these goals [1].

INTRODUCTION

The diagnostics requirements have been in several previously published papers [1,2,3,4]. There is a progression of ERL facility stages planned in order to move forward towards achieving full energy recovery. The diagnostics system configurations vary for each stage.

The initial stage called G5S includes the 2MeV SCRF gun, a straight beam transport to a superconducting rf cavities (SCRF) 5-cell, then two 20MeV beam transport lines to dumps, one straight beam line, the other with a 16^0 bend, shown in Figure 1.

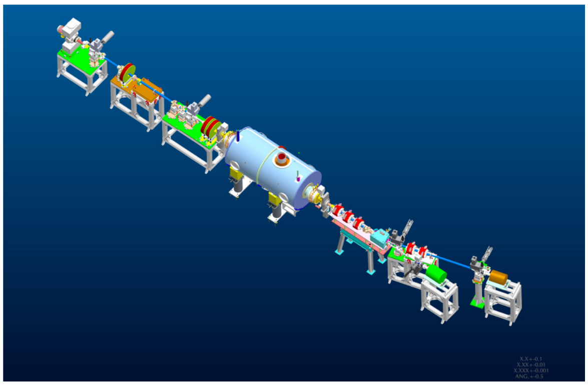

Figure 1: G5 Straight Layout

The second stage called G5 Zig-Zag (G5ZZ), see Figure 2, is similar to the first except the straight injection transport is replaced with more complex zig-zag configuration that is needed to provide an achromatic condition for the low-emittance, space charge dominated beam merger, and which is compatible with an emittance compensation scheme [K]. Both of the G5 stages are limited to 1uA operation by the relatively small temporary beam dumps.

The third stage includes all of the ERL subsystems, employs the ~20m full energy recovery loop, and a high power beam dump.

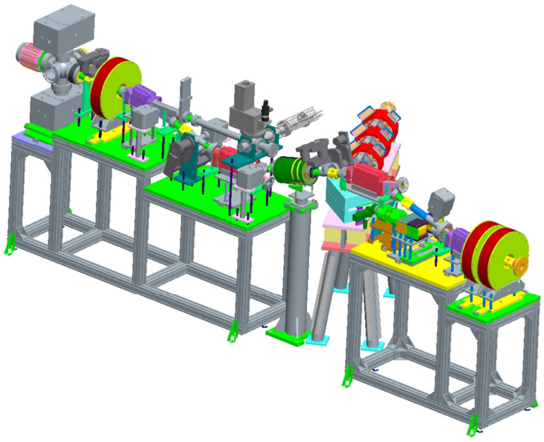

Figure 2: Injection Zig-zag transport between the gun and SCRF Linac, the beam path is left to right.

Due to the stringent requirements necessary to operate diagnostics near gun photocathodes that are sensitive to contamination, and near SCRF that may not hold voltage if particulates are present, extra effort (200C bake out, 10^{-11} torr, and Class 100 cleaning) is necessary during the design, fabrication, and installation process to ensure against any detrimental effects.

DIAGNOSTICS SYSTEMS

Beam Position Monitors

There are 16 dual plane 10mm diameter button style Beam Position Monitors (BPMs), 4 in the injection transport, 11 in the recirculation loop, and 1 in the dump line. The buttons are Times Microwave Systems model SK-59044; they are mounted on stainless cubes that are welded to the adjacent 6cm diameter beam pipes. The orientation of the cubes are installed either at 45^0 or 90^0 depending on their location. A 45^0 orientation is used if there are space limitations, and to avoid beam related energy deposition on a button downstream of bending magnets. The BPMs will be baked to 150C.

Libera Single Pass electronics from Instrumentation Technologies will process signals from the BPMs. These modules have been customized with a 700MHz SAW bandpass filter that matches the fundamental frequency of the SCRF gun and Linac accelerating cavities. A few fundamental characteristics of the Libera system are that it employs a digitizer with an 117MHz-sampling rate, a variable buffer length of 1k–8kB, a maximum trigger rate of 200Hz, and position threshold comparison beam inhibit output for machine protection. BPM signals will be transported to the signal processing electronics using Andrew LDF1-50 ¼" heliax cable to preserve the signal power at the 700MHz Libera passband.

When operating with typical ERL bunch trains of 9.3MHz, 351MHz, or 703MHz, performance parameters should be compatible according to simulations. Since the spacing between bunches in a bunch train spacing will be ~100ns or less, and the 700MHz filter will ring for >100ns, the individual bunch position will be difficult to distinguish within bunch trains.

The Libera BPM electronic units will be integrated into the standard RHIC control system. ADO (accelerator device object) software has been written and will execute directly on the Linux kernel that is resident in the Libera hardware. The ADO provides on-board communication to the Libera hardware through the CSPI (control system programming interface) library provided by I-Tech, and communicates to higher level workstations via Ethernet using standard RHIC control system utilities.

The BPM's on either side of the SCRF Linac will have trains of both high and low energy beams present during energy recovery mode, the different energy bunches will be separated in time by the loop transit time of ~60ns. We are considering several possible solutions. The first is to use a set of Bergoz MX BPM electronics that provides a 20ns wide measurement gate, and a beam synchronous trigger; the position data rates will be limited to 40kHz. The second method is to use a set of BPM pulse stretching preamps, and a 4ch fast oscilloscope to acquire position signals from the buttons. The oscilloscope data can be transferred via Ethernet and later processed elsewhere with LabVIEW.

Beam Profile Monitors

Transverse beam profiles will be measured by two methods, depending on the amount of beam charge in the bunch train. When in low charge operating mode with 1-100pC bunch charge trains, we will use 0.1 X 50mm YAG:Ce (yttrium aluminum garnet doped with Cerium) screens from Crytur (40mm clear aperture). For higher charge modes we will use OTR (optical transition radiation) screens that are comprised of a 250micron thick silicon wafer coated with ~1000 angstroms of aluminum. The profile monitor stations were specified by BNL and designed and fabricated by Radiabeam Technologies.

Images from the YAG and OTR screens are transported through a mirror labyrinth to a 3-motor lens and CCD camera in a local enclosed optics box. The Point Grey Flea2 1394b camera is planned for early operations. We are testing our ERL Linux Red Hat Controls [C] interface to a Grasshopper2 GigE camera that may prove to be more convenient for communications and long haul signal routing.

Due to the tight space constraints in the injection zig-zag transport the Radiabeam profile monitors will be reused in the high power dump beam line, in the ERL loop, and in the transport straight out of the gun. A more simplified YAG profile monitor will be designed to plunge into the beam path of the injection 30^0 dipole chambers through an auxiliary port.

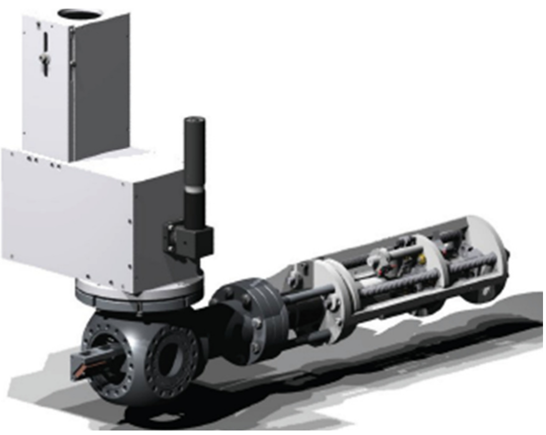

Figure 3: Profile monitor with 3-position actuator.

Synchrotron light monitors will be used to measure transverse beam profiles while running with high power beams. Due to the long wavelength of synchrotron radiation below 18MeV, using these monitors could be challenging. We plan to install optical transports and CCD cameras at a number of the ERL loop 60^0 dipole locations. The dipole chambers have dedicated synchrotron light output viewing ports.

Halo scrapers will be installed in the injection transport to measure the amount of beam in the halo. Horizontal and vertical pairs of stepper motor controlled 2mm thick copper jaws will be located at several locations in the injection transport. After the halo characteristics are measured, a collimator will be designed to scrape off the undesired halo at low energy to reduce higher power beam losses downstream.

Beam Emittance

There are three techniques planned to measure beam emittance at three locations. Expected normalized emittance range is 2-10um.

In the first method, a pepper pot station will be used to measure 2MeV beam emittance in the G5S injection transport. The pepper pot will be comprised of two plunging tungsten masks upstream of a YAG:Ce profile monitor, one located at 0.25m, and the other 0.5m.

The dynamic range of the emittance measurement will be limited by the space charge effect. The space charge effect can be characterized by the ratio of the space charge and emittance contribution in the beam envelope equation. Assume the rms beam size is 1 mm, normalized emittance is 2 mm·mrad, bunch length is 10 ps, for 2 MeV electron beam and 100 um wide slits the ratio exceeds 0.05 when charge per bunch reaches 60 pC. To produce enough light from downstream YAG:Ce screen, ~20 pC per bunch is needed for a single shot emittance measurement. Therefore, the dynamic range for the multislits is 20 to 60 pC per bunch. For a hole matrix mask, beam expansion due to space charge should be less

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than 5% of that due to the uncorrelated beam divergence. With 100 um diameter holes, beam divergence 10^{-3} rad, drift length 0.5 m, the upper limit due to space charge is ~550 pC per bunch.

The second method will measure 20MeV beam emittance in the transport straight out of the gun, using the traditional quad scan technique, and image data from the downstream YAG & OTR profile monitor. A quad triplet is located 2m upstream of the profile monitor.

The third method will also be made downstream of the 5-cell SCRF Linac; the 20MeV beam emittance will be measured in the 16 degree bend line using a longitudinal slice emittance technique during the G5S & G5ZZ test configurations. There are 2 plunging profile monitor stations downstream of the 16 degree bend. The upstream station will have a 500u wide slit installed in one of the two diagnostics insert positions. The second insert position is an OTR screen for profile measurements at that location.

With this 500u wide slit inserted, and while acquiring image data from the profile monitor 2m downstream, the following parameters will be scanned: rf phase of the 5-cell cavity, upstream dipole, and downstream doublet quadrupole magnet strengths.

Beam Current Monitors

High precision DC current measurements will be made using a matched set of Bergoz NPCT-S-115 DC current transformers (DCCT) and standard NPCT electronics. There will be one each installed in the injection and extraction transport beam lines. These DCCTs are configured in a nulling mode [3] where their calibration windings are joined in a single loop, and driven opposite the beam by a low-noise Khronhite model 523 current source. The output level of the dump DCCT is fed back as a reference to the current source to drive the dump DCCT output to zero. The output of the gun DCCT is then a differential current measurement.

We are presently considering several signal processing and data analysis hardware solutions from National Instruments for handling DCCT system tasks that include absolute and differential measurements. Drift (magnetic field, thermal, and gain) compensation will be automatically removed by periodic nulling without beam. The anticipated submicroamp resolution may permit using this diagnostic as a second layer of the machine protection system [A] in the case the beam loss monitors fail to detect beam losses.

It is important to avoid high-frequency harmonics from entering the cavity formed by the transformer and its enclosure. In other installations at C-AD, the solution was to install a distributed capacitor ring around the ceramic gap. For the ERL assembly, besides the DCCT, we also have a bake out heating blanket and water-cooled ring inside the magnetic and electrostatic shielding, leaving little space for a robust capacitor ring. We developed a capacitor using kapton tape sandwiched between two aluminum cylinders. It was heated several times to 250C, and tested in between each bake to make sure its value and frequency characteristics were stable.

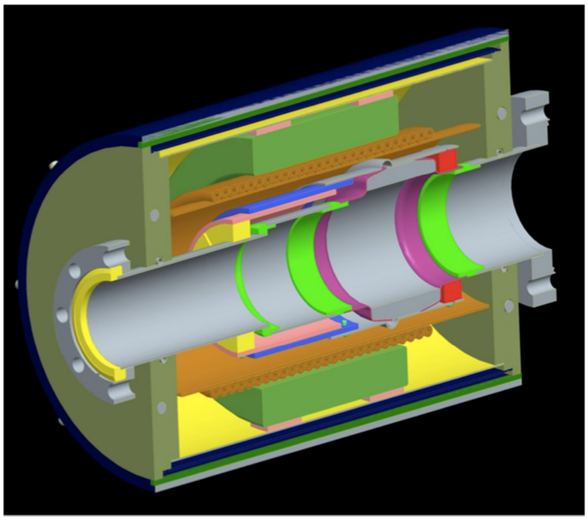

Figure 4: DCCT Assembly. Includes NPCT toroid, with capacitor, cooling coils, ceramic break, and magnetic shielding enclosure.

Two more capacitors were then constructed and baked, and ultimately we chose two for installation, one per DCCT assembly, that were the most closely matched of the three constructed. The assembly is shown in Figure 4.

Bunch-by-bunch & bunch train charge will be measured by a Bergoz in-flange Integrating Current Transformer (ICT) part number ICT-CF6-60.4-070-05:1-H-UHV-THERMOE, located in the upstream injection line. This ICT assembly has internal type E thermocouple for bake out (to 150C) temperature monitoring; this feature was added by request.

Beam charge signals will be processed by standard Bergoz BCM-IHR Integrate-Hold-Reset electronics feeding a beam synched triggered digitizer. The maximum integrating window in the ICT electronics is 13.1us, and the minimum window is 200ns. The triggering frequency is independent of the integrating window size. We have tested the BCM-IHR modules to trigger at a maximum frequency of 150Hz, but may need to reassess our trigger frequency needs as beam modes become more defined.

Care must be taken during bake out of the regions containing the DCCTs and ICT. When the magnetic core is heated beyond 100C, irreversible modifications occur. This does not mean one cannot exceed 100C with proper precautions (such as a cooling water loop), but the immediate outcome of high core temperature is a loss of magnetic permeability scaling with temperature. At 168C, there would be an irreversible 50% permeability loss, with the consequence being an increase of output droop. The extent of the output droop depends on the transformer's turns ratio. For the ICT with 5:1 turns ratio and 50% permeability loss, droop is about 12%/us. Depending on the beam profile, an increased droop may or may not have adverse consequence. Output for a CW beam will be differentiated twice sooner, which does not make any practical difference. Output of a pulsed beam may see the zero baseline drift during the first milliseconds then stabilize [7].

Beam Loss Monitors

Photomultiplier tube (PMT) based loss detectors will be installed at locations where beam loss is most likely. The design of this detector is based on ones developed at Jefferson Lab and used at CEBAF [Z] and also for the 12GeV Upgrade [Y]. JLAB used the 931B PMT; a more modern tube was chosen for ERL. The Hamamatsu R11558 side-on tube is very similar to the 931B and has lower dark current, higher gain, and improved anode and cathode responsivity. The PMT was installed in light tight PVC housing containing a 10mA green LED for testing with 1uS light pulses.

In an effort to extend the use of the existing RHIC BLM System [X] processing electronics to the ERL, a preprocessing VME module had to be designed. As the RHIC BLM front-end V119 typically takes loss signals from positively biased ion chambers, the characteristically negative signal from the PMTs had to be inverted. Thus a custom interface for the VME chassis was developed containing eight independent channels of inverting amplifiers with integration matching that of the V119 card, and having an output stage for driving the capacitive input of the V119 card. A maximum gain of 200 was demonstrated with good signal to noise ratio. The interlock response time to a loss signal that exceeds a programmable threshold is ~10us. The actual PMT gain at each location will be field adjusted by setting the high voltage bias during beam commissioning. A CAEN HV multi-channel chassis with full remote control will bias the PMTs.

Eight Ion Chamber (IC) loss detectors, as currently used in RHIC, will be employed at select locations in ERL. These are 113cc glass bottles [W] with BNC & SHV connectors for signal and bias. These will be collectively biased to 1400V in two groups by two Bertan 205B-03R 3kV 10mA rack mount power supplies. The signals from each IC are transported on 75 ohm cables to the V119 modules. All V119 modules (PMT and IC connected) are supervised by a V118 module that monitors integrated signal level data compared to thresholds. The V118 module has a discrete loss output signal that will signal the machine protection system in the event of detected loss from any of the PMTs or ICs.

Ion chamber type loss monitors based on gas filled heliax cable, as used in the AGS ring [V], will be employed at ERL. The cable is 7/8 inch Heliax, Andrews type RG318, filled with Argon to 10 psig. Four long loss monitor cables will run along the inside of the loop while 12 short loss monitor cables will hug the outer casing of the final beam dump. The cable loss monitors are biased to ~150V by custom floating bias supplies (used in the AGS), mounted in NIM modules. The loss signal returns on the bias cable and is integrated by a custom integrating amplifier modules (also used in the AGS) whose analog outputs are digitized by standard VME DAC modules.

In addition to amplitude proportional beam loss detection, as provided from the PMT, IC & Heliax detectors, event count based detectors are employed. PIN Diode loss detector modules, Bergoz model BLM, will be installed at eight select locations in ERL. These modules are built around two PIN photodiodes mounted fact-to-face making use of coincidence counting to be insensitive to synchrotron radiation photons. With extremely low spurious count rate of < 1 in 10 sec, up to 10 MHz counting, dynamic range of 10^8, and 100nS recovery time, these detectors are of the lowest costs and highest dynamic ranges available [8]. The TTL data output of each detector is counted by a Struck model SIS3808 scalar VME module.

Thermal imagers will be used at several locations to measure beam pipe temperature gradients to ensure beam losses not seen by other loss detectors are monitored. We chose the FLIR A310 camera. It offers image transfer and control via Ethernet, and configurable location specific temperature thresholds on the image can be programmed and used to provide a machine protection alarm or interlock signal from a digital output port on the camera assembly.

FUTURE INSTRUMENTATION

We plan to eventually add more instrumentation systems as the progress with the ERL facility moves forward. These systems in include a streak camera, M_{56} measurement using a longitudinal BTF technique, and several techniques to measure high power transverse beam profiles. There is beam transport space available in the ERL loop far from the SCRF cavities. We are considering using conventional wire scanners, vibrating wire scanners, and laser wire scanner techniques. A combination laser wire with Compton photon counter can be used to measure all three dimensions of the electron bunches in the high power regime.

STATUS AND SCHEDULE

First electron beams in the two phases of the Gun to 5-cell transport are planned for early 2012. We are scheduled to install the ERL loop beam line components after the G5 tests are complete.

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