Table 2.9.1: ERL flight distances and flight times

Location (Time of Flight)	Distance from Gun (m)	Time-of-Flight from Gun (μs)
Injector (T_{I})	20.61	0.069
Linac A [first pass] (T_{LA1})	364.34	1.215
Turn-Around A (T_{A})	523.64	1.747
Linac B [first pass] (T_{LB1})	808.44	2.697
S, N, & CESR Arcs (T_{CESR})	2050.95	6.841
Linac A [second pass] (T_{LA2})	2394.67	7.988
Turn-Around B (T_{B})	2552.04	8.513
Linac B [second pass] (T_{LB2})	2837.84	9.466
Beam Stop (T_{STOP})	2846.09	9.494
		Time-of-Flight from Injector (μs)
Re-circulation (T_{RECIRC})		6.773

2.9 Start-up Procedures

An ERL requires a start-up plan that is different from those employed for either Linacs or storage rings. The laser-driven photo-cathode has some limitations on bunch patterns that can be produced; the injector's optics are strongly influenced by space charge and beam loading of the injector RF cavities. This implies that during final setup procedures the charges of the bunches should be close to the design operating level, and since the SRF cavities in the two main Linacs have high loaded Q's, beam loading of the cavities will produce a significant energy slew across a long bunch train when operating in a non-energy-recovery mode. When energy recovery is first initiated, the timing and pattern of bunches must be controlled accurately to avoid additional energy variations from bunch-to-bunch or train-to-train. Some of the instrumentation requires special bunch patterns to function correctly. Finally, during the current ramp-up mode, the beam loading of the main Linac cavities limits the rate at which charge may be added to beam.

Figure 2.9.1 is a schematic layout for the ERL complex and includes a simplified illustration of the trajectory of an electron bunch within the ERL. The bunch begins at a time T_0 in the injector, passing through the merger before reaching Linac A at time (T_{I}), and then completing one pass through Linac A (T_{LA1}), Turn-Around A (T_{TA}), Linac B (T_{LB1}) and the CESR Arc (and south and north arcs) before returning to the entrance to Linac A at time (T_{CESR}). At this location in the circuit a high-energy beam stop is placed for use when the bunch is not undergoing energy recovery. In the energy-recovery mode, the bunch will continue through Linac A (T_{LA2}), Turn-Around B (T_{TB}), Linac B (T_{LB2}), and the Beam Stop (T_{STOP}). There is also an intermediate energy beam stop placed after the turn-around arcs to allow for the adjustment of the turn-around arcs before injecting the beam into Linac B. The time the beam takes to recirculate, i.e. go through Linac A, Turn-Around A, Linac B, the South and North Arcs and CESR, returning to the entrance for Linac A, is $T_{\mathrm{RECIRC}} = T_{\mathrm{CESR}} - T_{\mathrm{I}}$, and for the current design this is approximately 6.8 microseconds. The detailed times are given in Tab. 2.9.1.

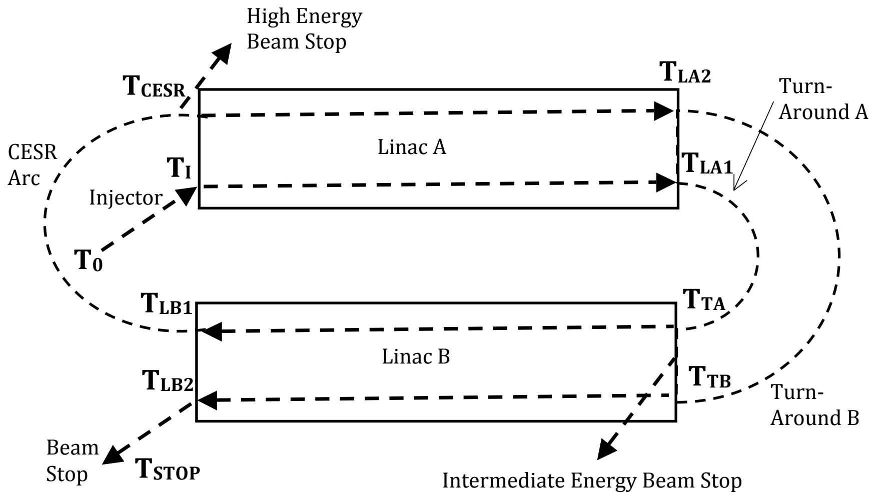

Figure 2.9.1: Functional block diagram of a bunch's traversal of the ERL.

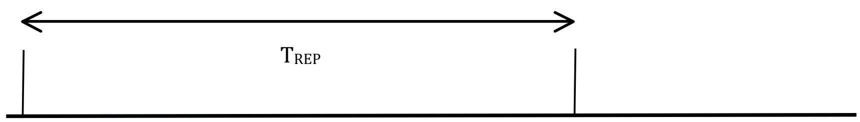

Figure 2.9.2: Bunch pattern during the first-turn-steering mode of operations.

First turn steering

Because space charge and beam loading effects in the injector are important, its tuning will be done with the design bunch charge of 77 pC. The first turn steering of a single bunch from the injector through the rest of the ERL will be accomplished by using the BPM system and screens that can be inserted into the accelerator aperture. With a $4 \times 60\,\mathrm{Hz}$ repetition rate beam (see Fig. 2.9.2), the high energy beam stop will need to be capable of an average beam power of $5\,\mathrm{GeV} \cdot 77\,\mathrm{pC} \cdot 240\,\mathrm{Hz} = 100\,\mathrm{W}$. The intermediate energy beam stop at one half the beam energy could receive one half of the beam power (50 W). The actual power levels will be determined by the dark current and the limited extinction ratio of the laser that will have to be determined experimentally. During this process, as the train of bunches passes by beam position monitor (BPM) detectors for the first time, the timing of the detection of the signal will be established for each BPM processor. When it is completed, this mode of operation will have seen the adjustment of the Linac phasing, the centering of the trajectory to within several millimeters of the final trajectory and the first correction of the optics in the complete accelerator except for Turn-Around B.

First turn accelerator setup

In order to complete the beam trajectory through the ERL, bunches with the proper delay of their arrival time will pass through Linac-A on the decelerating phase, Turn-Around B,

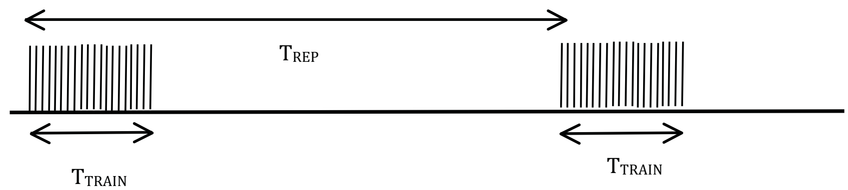

Figure 2.9.3: Bunch pattern during the first-turn-accelerator-setup mode of operations.

up to the Intermediate-Energy beam stop. After orbit and basic optics corrections through Linac-B, the beam's arrival time will be adjusted to the decelerating phase and transported to the beam stop. After the beam has been tracked up to the final beam stop and the timing for the BPM processing has been confirmed, more precise position measurements and corrections will be undertaken by both single trajectory and average trajectory acquisitions. As shown in Fig. 2.9.3, the beam is modulated to be a train of 77 pC bunches spaced at 1.3 GHz of duration T_{TRAIN} (e.g. approximately 100 ns), long enough for the BPM system and other diagnostics to function more accurately to give the average train parameters, and short enough for beam loading of the Linac sections ($\delta p/p = 2 \times 10^{-5}$ per bunch) to not produce a very large energy spread across the train. The repetition period for the trains is T_{REP}, which is again harmonic with T_{RECIRC} and is capable of being locked to low harmonics of the AC line frequency. The envelope of each train's current should have reasonably flat amplitudes for many tens of nanoseconds during the time-slice used for the beam measurements. In this mode, the offsets of the BPMs with respect to the quadrupole centers would be determined and dispersion free trajectory corrections would be applied. Then the focusing optics can be measured using response matrix techniques and corrections may be applied to bring the optics into agreement with the accelerator's design model.

Low power energy recovery

Utilizing the bunch pattern shown in Fig. 2.9.3, the timing of the bunches recirculating back through the Linacs, can now be refined. This will be accomplished by comparing the phase transients in Linac-A and Linac-B in the time just before the accelerating-pass and after the decelerating-pass of the bunch train, or by minimizing the required forward power to the cavities. The beam transport efficiency must also be taken into account before using this to adjust the path-length delay for the proper energy recovery arrival time.

Energy recovery accelerator setup

After taking the train of bunches through the entire circuit of the ERL, a second train of bunches is added with a delay of T_{RECIRC} (Fig. 2.9.4) Since there will be energy recovery in Linac-A and -B from the first train of bunches, the beam loading of the RF cavities will be compensated and the energy of each of the bunches in the second train will be nearly the same throughout the train. Assuming that the energies of Linac-A and Linac-B are increased slightly to account for the beam loading of the first train, then more precise orbit, optics, and time-of-flight corrections can be applied by measuring the beam parameters of the energy-

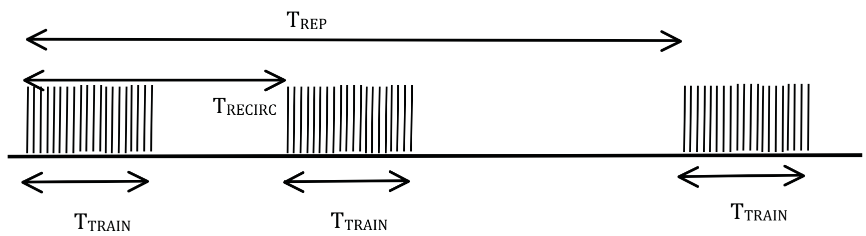

Figure 2.9.4: ERL bunch pattern for the Energy recovery accelerator setup-mode.

recovered part of the bunch train. At this point the position feedback loops can be placed in operation.

Current ramp-up

Having established the parameters for the ERL with a train of bunches operating with energy recovery, the ERL will be poised to ramp up the current to full CW operation. This will be accomplished by adding a trailing train spaced by T_{RECIRC} after each of the set of bunch trains already in operation. To reduce beam loading of the Linac RF cavities, additional trailing trains will be added in time intervals equal to approximately the Linac RF cavity filling time ($\sim$ 16 ms). So the time it will take to add trains (spaced by T_{RECIRC}) to fill in the gap between repeated trains, T_{REP}, will be $T_{\mathrm{REP}}^2/T_{\mathrm{RECIRC}} = (16\,\mathrm{ms})^2/6.77\,\mu\mathrm{s} = 37\,\mathrm{s}$. At this point there will be a continuous set of trains of length T_{TRAIN} spaced by T_{RECIRC} and the energy of all bunches will be the same since the Linac RF cavity beam loading will be compensated by the second pass of each train through the Linac cavities.

The final step of the current ramp-mode will be to fill in the gap $T_{\mathrm{RECIRC}} - T_{\mathrm{TRAIN}}$ between trains. Assuming that an additional set of bunches of duration T_{INC} will be added every T_{REP}, this step will take a time of $T_{\mathrm{RECIRC}}/T_{\mathrm{INC}} \cdot T_{\mathrm{REP}} = 6.77\,\mu\mathrm{s}/40\,\mathrm{ns} \cdot 16\,\mathrm{ms} = 2.7\,\mathrm{s}$.

In normal operation when the ERL begins to ramp its current after the accelerator parameters have already been established, the only difference from the preceding procedure will be to begin with the beam having the train spacing used in the Energy Recovery Accelerator Setup-mode (Fig. 2.9.4). After a pause to make certain all feedback loops are operating correctly, the current will be ramped in the two steps described in the preceding paragraphs of this section. These two steps for incrementing the current will take approximately 40 seconds to complete.

Laser considerations

In order to execute the startup procedure described in the preceding sections, the laser must be capable of producing light pulses for bunches having the required time structures. This is accomplished by hardware for two distinct laser-pulse timing patterns. During the ERL Injector Phase 1-A tests, beams with the same time structures as these bunch patterns have been in routine use. The first of these laser setups generated trains of bunches with a 50 MHz repetition rate and could be gated for various numbers of bunches in the trains. To generate the single bunches needed for the first-turn-steering mode of operation (Fig. 2.9.2), the laser will be gated to generate for a train having only one bunch. The second of the laser setups created trains of 1.3 GHz spaced bunches of various lengths, routinely operating with train lengths up to hundreds of microseconds long at a 60 Hz repetition rate. In the Phase 1-A laser system configuration, the Pockels cell modulator driver was not capable of operating at a 160 kHz repetition rate and smoothly transitioning to full duty cycle for the bunches. We are in the process of designing a gating scheme, which is capable of the parameters required for the bunch patterns specified above.

Beam loss considerations

In addition to using the intermediate and high-energy beam stops upstream of the Linacs, to minimize the damage and radiation from beam particles lost during the establishment of initial conditions for the first operation of the ERL, the train of bunches will be operated in a 'single shot' mode. In this mode the BPM and other beam instrumentation systems would record the beam's trajectory, RF phase transients, radiation loss location, and accelerator parameter corrections before injecting any subsequent train of bunches.

As part of the first tune up of the ERL beam, the beam abort system will need to be commissioned before continuing with first turn accelerator setup in order to protect sensitive components when the beam operates at the higher repetition rate.

ERL BPM system specifications

There are five different modes of operation of the ERL needed to take conditions from injecting the first beam through routine day-to-day operations. The beam position monitors will be located next to quadrupoles at locations that are optimum for Singular Value Decomposition (SVD) based beam orbit correction schemes. In the Linac and parts of the turn-around arcs there will be both the accelerating and the decelerating beams and it will be necessary to measure the position of each beam independently.

1. **First turn trajectory**
   - Objective: To transport a low-power beam from the injector to the high-energy stop immediately before a return to Linac-A for deceleration in order to measure and roughly correct the trajectory and optics. The high-energy beam power is limited to 100 W plus the dark current and laser extinction.
   - Bunching pattern: Single 77 pC bunch at a 240 Hz repetition rate.
   - Goal for BPM resolution:

     $\pm 1\,\text{mm}$ at 240 Hz readout

     $\pm 100\,\mu\text{m}$ at 2.5 Hz readout
2. **First turn accelerator setup**
   - Objective: To transport a low power beam from the injector to the high-energy stop immediately before the return to Linac-A for deceleration in order to measure and to begin to refine the trajectory and optics and to start setting up the slow orbit feedback. The high-energy beam power is limited to 100 W.

- Bunching pattern: Single 77 pC bunch at a 240 Hz repetition rate.
- Goal for BPM resolution:

  $\pm 100\,\mu$m at 240 Hz readout

  $\pm 10\,\mu$m at 2.5 Hz readout

3. **Low-power energy recovery**
   - Objective: To transport a low-power beam (< 100 W) from the injector to the final beam stop after deceleration in Linac-B in order to measure and roughly correct the trajectory and optics. The low beam power is to allow for the beam being lost before reaching the beam stop.
   - Bunching pattern: Single 77 pC bunch at a 240 Hz repetition rate.
   - Goal for BPM resolution:

     ± 1 mm at 240 Hz readout

     $\pm 100\,\mu$m at 2.5 Hz readout

4. **Energy recovery accelerator setup**
   - Objective: To transport a low power beam from the injector to the final beam stop after deceleration in Linac-B in order to measure and to continue to refine the trajectory and optics and to start setting up the slow orbit feedback in the return loop.
   - Bunching pattern: Multiple trains of 77 pC bunches (duration ~ 100 ns) with a $6.7\,\mu$s spacing operating at a 240 Hz repetition rate.
   - Goal for BPM resolution:

     $\pm 100\,\mu$m at 240 Hz readout

     $\pm 10\,\mu$m at 2.5 Hz readout

5. **Current ramp-up**
   - Objective: To transport a beam of increasing power, from the injector to the final beam stop after being decelerated in Linac-B in order begin energy recovery. The beam is in a train of bunches in a pulse of duration from 80 ns to continuous, operating at a 240 Hz repetition rate. As the average beam current is increased the trajectory and optics and slow orbit feedback are further corrected.
   - Bunching pattern: 77 pC bunches spaced at 1.3 GHz in trains of duration increasing from 80 ns to continuous, operating with a 240 Hz repetition rate
   - Goal for BPM resolution:

     $\pm 100\,\mu$m at 240 Hz readout

     $\pm 10\,\mu$m at 2.5 Hz at all times for slow orbit observations / feedback

     $\pm 0.3\,\mu$m at 1 kHz after reaching continuous beam current operation for slow orbit feedback