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STUDY OF BEAM POSITION MONITORS FOR PERLE

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on behalf of PERLE project team

Abstract

PERLE is an Energy-Recovery Linac (ERL) to be constructed at the IJCLab in Orsay. It will be the First multi-turn ERL with superconducting RF (SRF) with the ambition to reach 5 MW beam operation (20 mA beam current and 250 MeV beam energy). Diagnostics are a key element for PERLE operation and among diagnostics, the salient feature for Beam position monitors (BPMs) is the presence of multiple beams which need to be individually diagnosed and controlled. This document describes the study of PERLE BPMs with particular attention given to how these BPMs will handle multiple beams during commissioning and under normal operation of PERLE.

INTRODUCTION

PERLE facility is a new generation energy recovery machine covering the 10 MW power regime with 20 mA beam current and 500 MeV beam energy [1]. It is a compact multiple pass ERL based on SRF technology, to serve as testbed for validation and testing a broad range of accelerator phenomena and technical choices for future projects.

An overview of PERLE is sketched in Fig. 1. The photocathode gun is on the far right with the injector section immediately following. In this configuration, the peak beam energy is 250 MeV. This is achieved by passing three times through a SRF cryomodule.

Starting from a 7 MeV injector, the beam gains 82.2 MeV per turn, reaching successively 89 MeV, 171 MeV and a final energy of 250 MeV after 3 recirculation passes. After a path length shift of exactly half of RF period, it is then decelerated through the same linac structure to recover the beam energy up to the final dump at 7 MeV, thereby demonstrating full multi-pass energy recovery at high current.

Looking further ahead, an additional phase of the project is being considered. This upgrade would involve the installation of a second cryomodule in the second straight section, as originally foreseen in the conceptual design report.

PERLE CONSTRUCTION PHASES

PERLE is currently under construction in the IGLOO building at the IJCLab in Orsay, France. The project is progressing in successive phases, each designed to validate a key step toward the full ERL operation.

The first phase, scheduled for late 2028, focuses on commissioning the injector. This includes testing the high current electron gun, aiming to deliver up to 20 mA of 350 keV electron bunches at a repetition rate of 40 MHz, as well as the superconducting RF booster that accelerates these bunches to 7 MeV. During this phase, the merger section and a diagnostic mirror line will also be constructed and tested to ensure that the beam properties meet the design specifications.

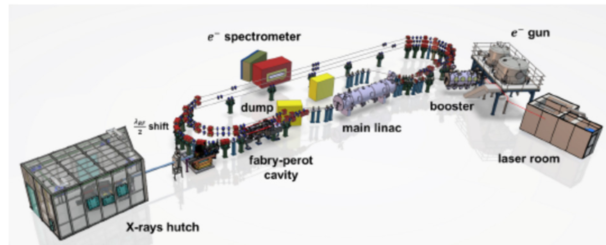

Figure 1: An overview of PERLE.

The second phase, expected to begin in 2029-2030, will establish and test the one-turn ERL loop. Key objectives of this phase include:

- Calibration of the linac.
- Fine tuning of the beam path length to ensure a maximum energy recovery efficiency.
- A first energy recovery with 89 MeV, 20 mA beam.

The third phase will implement the full three-turn, 250 MeV ERL configuration. Key objectives of this phase include:

- Achievement of 5 MW of energy recovery with 250 MeV, 20 mA beams.
- Demonstration of multi-pass high power energy recovery.

Beam Positions Monitors (BPMs) are a major diagnostic that would ensure a proper operation of PERLE along its construction phases, also for PERLE key components commission and PERLE operation.

The scope of this document is to detail BPMs specifications and operations at different stages of PERLE.

BPM FOR PERLE INJECTOR

Based on beam dynamics studies, BPM locations are mentioned in Fig. 2.

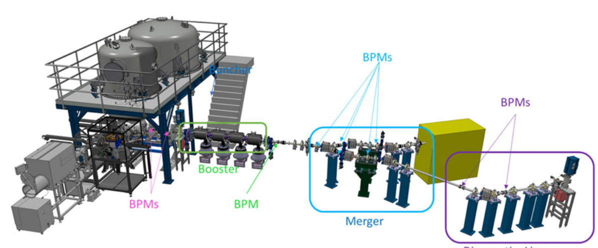

Figure 2: Injector BPMs locations.

As mentioned above, the injector aims to deliver up to 500 pC beam charge with a repetition rate of 40 MHz; the bunch length is about dozens of ps. However, for injector

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commissioning, the "worst" beam scheme should be a 10 MHz repetition rate beam with a charge down to 10 pC.

Besides the "green" BPM, all the others do suffer from a quite stringent housing (less than 200 mm for BPM and steerers in the merger). Therefore, button BPMs seem to be the most suitable with such small available space. BPM diameter is set equal to beam pipe diameter (presently 60 mm) and each button diameter is set to 11 mm. Based on CST simulations [2], BPM output characteristics for the worst beam scheme are shown in Table 1.

Table 1: Injector BPM Characteristics

Output peak [V]	Position Sensitivity [dB/mm]
0.1	1.18

Position measurement is needed; this measurement is standardly performed on a given frequency f_1. Position measurements from 2 BPMs separated by a dipole can be combined to deliver beam energy. For post booster BPM (in green in Fig. 2), beam longitudinal length measurement is required. This is performed by acquiring button output level for a centred beam at two different frequencies f_1 and f_2 [3]. The frequencies mentioned above should be chosen based the following criteria:

- Quite strong BPM output signal at these tones (over -40 dBm for the simulated worst case).
- Frequencies are not too high to allow affordable acquisition electronics.
- Frequencies are both multiples of 40 MHz.
- Frequencies not too close for a better resolution of beam longitudinal length measurement.
- Frequencies where "off the shelf" RF components are available: particularly during commissioning where band pass filters with less than 10 MHz bandwidth might be needed.

BPM FOR ONE-TURN ERL LOOP

BPM locations are shown in Fig. 3. Those BPMs are:

- Linac BPMs: 2 BPMs at the Linac entrance and exit.
- Loop BPMs: 14 BPMs along the loop.

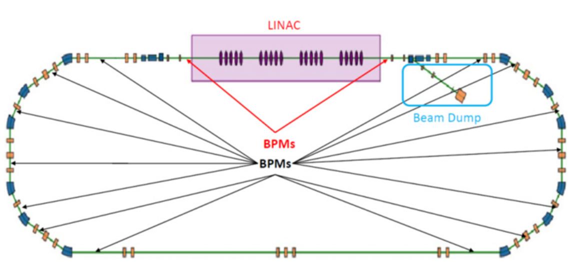

Figure 3: BPM locations for 1 turn ERL loop.

Beam scheme and specifications for the 14 BPMs are the same as for injector BPMs. These BPMs are almost the same as for the injector but with a reduced diameter (40 mm instead of 60 mm). Their outputs characteristics for the worst beam scheme are shown in Table 2.

Table 2: One-Turn Loop BPM Characteristics

Output peak [V]	Position Sensitivity [dB/mm]
0.4	1.73

Their acquisition electronics should only measure beam position.

In normal operation, the beam scheme for Linac BPMs is sketched in Fig. 4, with D = 3.125 ns and D' = 21.875 ns.

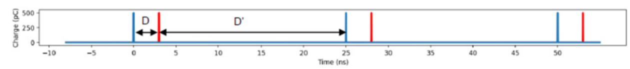

Figure 4: Beam scheme for Linac BPMs.

There are two beams "seen" by these BPMs:

- The blue one refers the accelerated, or to be accelerated beam.
- The red one refers to the decelerated, or to be decelerated beam.

Linac BPMs are chosen to be the same as for the injector. The button output in time domain is sketched in Fig. 5.

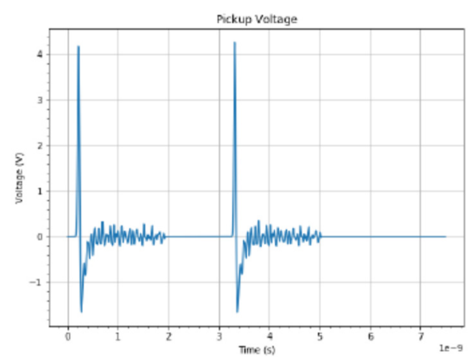

Figure 5: Linac BPMs button output in time domain.

Beam Position Measurement

Concerning Linac BPMs, the positions of both beams should be calculated and distinguished. A possible solution, inspired from BPM design for CBETA [4] is to acquire at least a single ADC sample on the peak of the selected energy bunch will be acquired for each of the 4 buttons signals. Many samples will be averaged in order to limit the sample-to-sample variations of the reported measurements.

For this solution, ADC clock should be addressed carefully. In order to align the ADC sample to the peak of the selected energy bunch, the ADC clock should be locked to the RF clock. Therefore, a stable clock is essential. Several configurable timing parameters should be used to configure ADC clock to the peak of the selected energy bunch.

Once ADC clock is fixed, then specific delays should be applied to ADC clocks delays.

Note that none of the energy passes have the same delay time of the ADC clock, so the timing phases must therefore be different for each beam. Thus, only one of the 2 beams energies can be measured at a time, and timing values must change in order to measure the other beam.

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For the Loop BPMs, a single beam is monitored, therefore, injector BPMs acquisition system is used.

Path Length Monitoring with Linac BPMs

As mentioned above, fine tuning of the beam path length is mandatory to ensure a maximum energy recovery efficiency. Once this path length is adjusted, Linac BPMs output voltage spectrum shows nodes at odd multiples of 160 MHz. The level of button output at these nodes can be used to correct path length of one-turn ERL loop.

As shown in Fig. 6, the level of the 800 MHz tone reaches a minimum for a 3.125 ns delay.

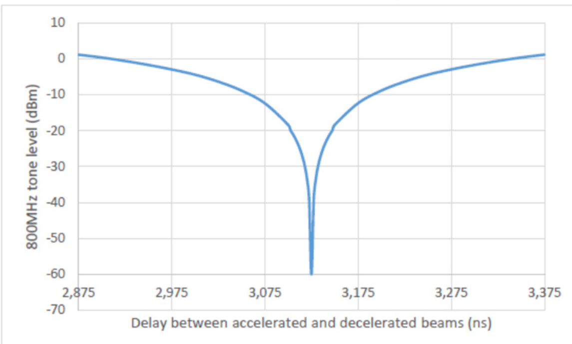

Figure 6: Level of 800 MHz tone vs delay between accelerated and decelerated beams.

Phase Measurement with Linac BPMs

In order to calibrate cavities phases in the linac, there is a possible operation [5] using beam phases with respect to the reference signal at Linac BPMs. Theses phases should be measured with the BPMs located at Linac entrance and exit. However, in normal operation mode, the two beams induce a different pickup output signal from a single beam. The phase of this signal w.r.t to the reference signal cannot distinguish accelerated beams from decelerated beams.

As the calibration of the cavities of the Linac can be performed during commissioning, a specific beam scheme is defined for this calibration. This beam scheme will need a specific operation scheme of Linac BPMs.

Beam scheme should be managed in accordance with specific Linac BPMs acquisition gates so that Linac cavities phases can be calibrated both in acceleration and deceleration modes.

BPM FOR 3-TURNS ERL LOOP

The BPMs are dispatched into 4 categories:

- Linac BPMs: 2 BPMs at the Linac entrance and exit.
- 89 MeV BPMs: 14 BPMs in the loop routing the beams with an energy of 89 MeV.
- 171 MeV BPMs: 14 BPMs in the loop routing the beams with an energy of 171 MeV.
- 253 MeV BPMs: 14 BPMs in the loop routing the beams with an energy of 253 MeV.

Position Measurement

In normal operation, the beam scheme for 3-turns ERL loop BPMs is sketched in Fig. 7. Concerning Linac BPMs, the positions of six beams should be calculated and distinguished.

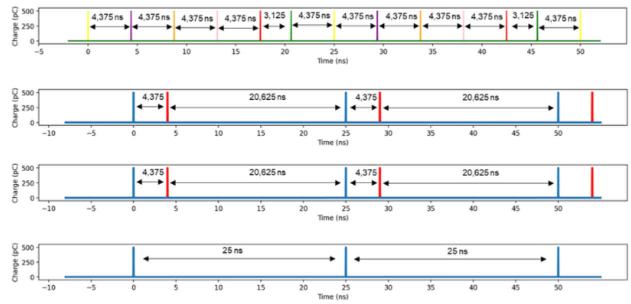

Figure 7: Beam scheme for 3-turn ERL loop, from top to bottom: Linac, 89 MeV, 171 MeV and 253 MeV.

The solution mentioned above is reused with a locked ADC clock and specific delays. We remind that only one of the six beams is measured at a time. Concerning 89 MeV BPMs and 171 MeV BPMs, the positions of the beams (two per loop) are measured in the same way. Concerning 253 MeV BPMs, a single beam is monitored, therefore, injector BPMs acquisition system is used.

Path Length Monitoring

Concerning 89 MeV BPMs as well as 171 MeV BPMs, their buttons output voltage spectrums show nodes at odd multiples of 800 MHz. The level of button output at these nodes can be used to correct path length of the loops routing 89 MeV beams and 171 MeV beams respectively.

NEXT STEPS

Button BPMs seem suitable for PERLE. Strong attention should be put on acquisition electronics. The front end should switch between two paths: full signal acquisition path or single tone filtering path. The firmware should also handle two schemes:

- Peak measurement scheme: acquire at least a single ADC sample on the peak of the selected energy bunch will be acquired for each of the 4 BPM pickup signals.
- Non-IQ processing scheme to be applied on single tone signals.

The characterisation of the BPMs with their acquisition systems should be performed on a specific test bench already available in the IJCLab facility.

CONCLUSION

The study of PERLE beam position monitors is reported. Button BPMs seem quite appropriate for the entire PERLE accelerator, however, attention should be put on housing issues in some locations. PERLE BPMs, at specific locations, should measure and distinguish the positions of multiple beams (up to six beams). They should also measure beam phase for Linac cavities calibration and also measure beam energy and longitudinal length. All these features make BPM acquisition system quite sophisticated. The experience from BPMs in other ERLs was of great help in this study and the future design and realization of PERLE BPMs and their acquisition systems.

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