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TOWARDS OPTICS MEASUREMENTS WITH A NEW LEIR BPM SYSTEM

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Abstract

The LHC Injector Upgrade (LIU) programme forms a cornerstone of the High Luminosity LHC project. Among its targets, a new BPM system has been deployed in LEIR to facilitate new optics measurements. This paper reports on the commissioning and analysis of turn-by-turn data from the new BPM acquisition system. Furthermore, the specific challenges and current limitations in LEIR for achieving long-term coherent excitations with sufficient amplitude for optics measurements are discussed, as well as some of the optics measurements performed so far.

INTRODUCTION

The Low Energy Ion Ring (LEIR) is the first synchrotron in the heavy ion accelerator chain for the LHC, and achieved its target parameters for the LHC Injector Upgrade (LIU) at an early stage [1–4]. The main parameters are summarized in Tab. 1. As part of the LIU upgrade, a new Beam Position Monitor (BPM) acquisition system has been deployed in LEIR and since the start of Run 3 the acquisition software has been further improved to facilitate detailed optics measurements from turn-by-turn data [5, 6], as well as exploring the various transverse beam excitation methods for optics measurements. This paper discusses the tests and activities undertaken to achieve the first optics measurements at flat bottom energy of LEIR in Run 3, using this new BPM system.

Table 1: LEIR Parameters for the Nominal Cycle after the LIU [1, 2]

Parameter	Value
Circumference	78.54 m
Rev. Frequency	0.36-1.41 MHz
E_{kin}	4.2 → 72.2 MeV/u
Capture Intensity (2b)	$12 \cdot 10^{10}$ charges
Extraction Intensity (2b)	$9 \cdot 10^{10}$ charges
Q_x, Q_y	1.82, 2.72

BPM phasing

In order to achieve accurate optics measurements, it is critical to have well phased BPMs. At the start of Run 3, The LEIR BPMs did not take into account the time delays arising from cable lengths and the time of flight of bunches between BPMs. The calculation of the specific delays for each BPM is based on the raw BPM data acquired at the last turn. At the moment of beam extraction, the raw BPM signals should be aligned such that the last detected bunches in each BPM all overlap. The compensation of cable length and time-of-flight delays cannot be done internally in the hardware, and is therefore carried out in the Front-End Software Architecture (FESA) class processing [7–9].

Initial measurements showed significant contributions from both cable length and time-of-flight delays, as shown in Fig. 1. Notably, a shift of up to 1 full turn was observed between the horizontal and vertical planes of some BPMs located at the same location in the ring. From the extraction energy and the machine geometry, the time-of-flight delay can be easily calculated. As the BPM sampling rate is locked to the RF cavity frequencies, this delay compensation is a fixed number throughout the LEIR cycle. Inversely, since the sampling frequency of the BPM system is varying, this results in a changing time compensation for the cable length offsets. The implementation of both the compensation of the time-of-flight and that of the cable length delays results in a properly phased BPM system, as presented in Fig. 1.

Limitations on total number of acquired turns

The BPM signal processing time is constrained to a single cycle to avoid overlap and interference with the following machine cycles, and thus limits the maximum number of acquired turns. At flat-top, around 90% of the processing time is spent on data readout, and is limited by the VMEbus in the acquisition system. The main reason for this, is that the LEIR BPM system does not have absolute knowledge of where the bunches are, and thus outputs 69 data points per machine turn for the peak detection. This sampling frequency comes from the ratio between the maximum beam revolution frequency and the maximum sampling frequency of the analog-to-digital converters. The easiest path to increase the number of turns in LEIR BPMs is thus to increase the available time for the processing of acquisitions.

Over the course of 2022, the maximum number of acquired turns has been increased from 300 turns to 1200 turns at flat-bottom energy, by advancing the start of the BPM signal processing earlier in the cycle. To achieve similar gains at top-energy, a long flat-top period of the cycle needs to be developed, or the hard time limit at the end of the cycle should be relaxed. Currently, only 300 turns may be acquired at top-energy.

The number of turns can further be increased by downsampling the data readout to once every n samples, effectively increasing the number of turns by n. However, increasing the decimation rate beyond 2 can significantly affect the BPM accuracy.

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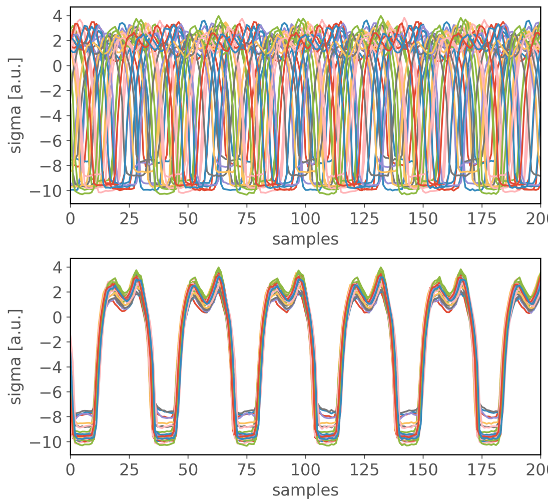

Figure 1: Comparison of raw BPM data before and after correction of cable length and time of flight delays.

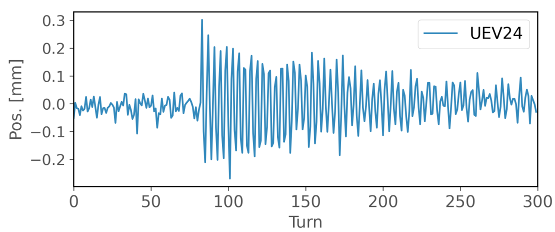

Figure 2: Transverse turn-by-turn obtained in BPM UEV24 from measurements with a 500 V kick in both planes using the tune kicker.

METHODS OF BEAM EXCITATION

Several methods are available in LEIR to provide coherent beam excitations that are necessary for optics measurements from turn-by-turn data. The LEIR beams can be excited with single kicks using the transverse damper, the tune kicker, or the extraction kicker [10, 11]. Furthermore, the transverse damper can be used in an ac dipole mode to provide forced transverse oscillations [12–14]. The following section presents the results from beam excitation tests at flat-bottom energy using the different excitation methods.

The tune kicker in LEIR provides single kicks and can be safely operated up to 500V. Figure 2 shows the oscillation amplitude in low noise vertical BPMs. The maximum peak-to-peak oscillation amplitude is around 0.5 mm. Beam oscillations with such limited amplitudes are only clearly visible in a few vertical BPMs. Therefore, reliable optics measurements cannot be performed with the tune kicker.

Single kick measurements with the transverse damper provided lower amplitude oscillations than with the tune kicker, and are therefore not shown here.

The extraction kicker [10, 11] is used to extract the beams at flat-top and can only kick in the horizontal plane. This kicker consists of 3 different kickers (namely ER.KFH31, ER.KFH32 and ER.KFH34) with their nominal strengths

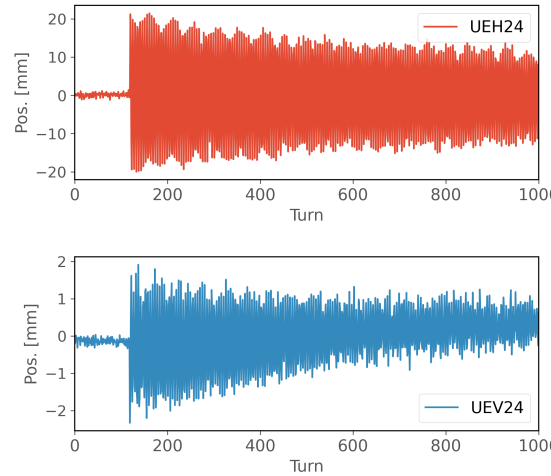

Figure 3: Transverse turn-by-turn obtained in BPMs UEH24 and UEV24 from measurements with a 13 kV kick in the horizontal plane.

at around 54 kV. The challenge of using this kicker is to advance the timing of the trigger, and to reduce its strength with the present control system.

Measurements were carried out with the minimal 13 kV kick strength using the ER.KFH32 kicker only, thus reducing the effective kick further. Figure 3 shows horizontal turn-by-turn data obtained from measurements with the extraction kicker ER.KFH32 at 13 kV. The data shows a clean large amplitude transverse oscillation. While the extraction kicker only excites the horizontal plane, leakage of the kick into the vertical plane can still be observed. The oscillation amplitude is significantly smaller than in the horizontal plane, but can still be detected in most BPMs. The bottom plot in Fig. 3 shows the maximum amplitude observed in vertical BPMs from leakage of the horizontal kick.

The transverse damper is used in operation for providing a chirp excitation to improve tune measurements. This mode can be adjusted to provide a slow amplitude ramp up and long flat-top excitation, yielding long coherent beam oscillations. The transverse damper in such an ac dipole mode will simply be referred to as an ac dipole. Measurements have been performed with the ac dipole at flat-bottom energy with a single 20 dB attenuator removed per plane. Figure 4 shows the turn-by-turn data obtained from such a beam excitation. The ac dipole provides sufficient amplitude for optics measurements in both planes. Furthermore, it is considered a viable option for optics measurements at top-energy due to the possibility of removing a further 20 dB attenuator per plane.

OPTICS MEASUREMENTS IN LEIR

The improvements implemented during the commissioning of the new BPM system, as well as the exploration of the different excitation methods, have allowed to perform the first optics measurements of Run 3 at flat-bottom en-

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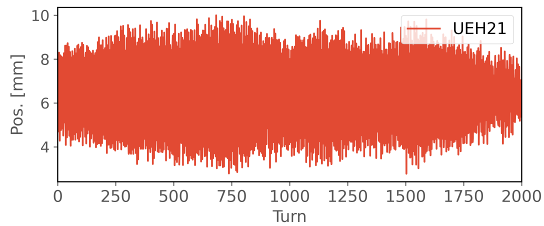

Figure 4: Horizontal turn-by-turn obtained in BPM UEH21 from measurements with ac dipole excitations. The number of turns is large as a decimation rate of 2 was used for these measurements.

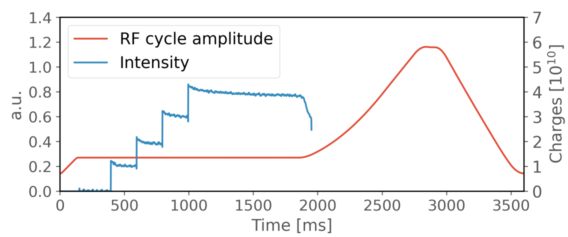

Figure 5: Measurement of beam intensity compared to the RF cycle in the dedicated MD6 cycle.

ergy in LEIR. Optics measurements at flat-bottom using the ac dipole and the extraction kicker are compared in this section. Both measurements were performed, after RF capture, at 1800 ms in the MD6 cycle, as shown in Fig. 5. The optics measurements are currently compared to the design model [15]. However, iterative and cumulative changes in LEIR caused the machine to deviate from the design optics models. As such, it will be necessary in the future to develop better knowledge of the machine model for more accurate optics comparisons.

Optics measurements were performed in the flat-bottom part of the cycle on a shot-to-shot basis in the MD6 cycle. An average can be taken over multiple shots to obtain statistically representative measurements of β-beating. Measurements with the ac dipole were only successful for very small tunes split between ac dipole and natural tunes, i.e. $Q - Q_{\mathrm{d}} \sim 0.001$. The measured optics could not be compensated for the ac dipole optics distortions due to the small tune-split, but such perturbations will be small ($\Delta\beta/\beta < 1\%$) [14]. Figure 6 shows the averaged $\Delta\beta/\beta$ for both the ac dipole (in both planes) and the extraction kicker (horizontal plane). The ac dipole measurements show a larger shot-to-shot variation compared to the extraction kicker, which translates into larger measurement errors. This may be attributed to the low tune stability causing varying amplitude responses to the ac dipole. In general, a very good agreement is observed between ac dipole and extraction kick measurements in the horizontal plane, with both methods showing equivalent β-beating and peak β-beating of 25%. In the vertical plane, the ac dipole measurements show a peak β-beating of 22%.

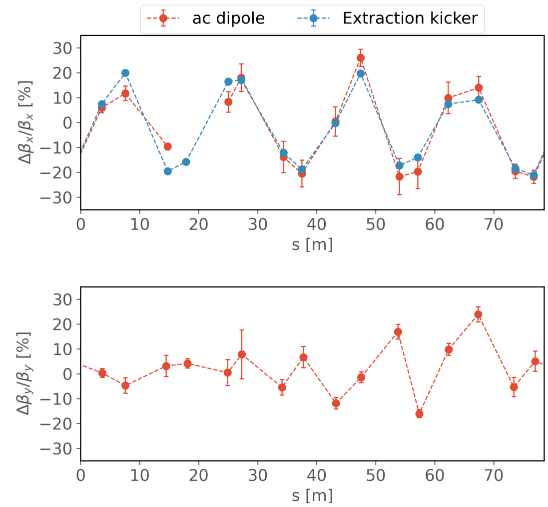

Figure 6: Horizontal and vertical β-beating measured with ac dipole excitations in red, and horizontal kicks with the extraction kicker in blue.

Figure 6 shows that using single kicks offers the most reproducible optics measurements shot-to-shot. This clearly motivates further studies to explore methods to obtain large amplitude single kicks in the vertical plane, either by increasing the available voltage in the tune kicker, or by stabilising the leakage of the extraction kicker into the vertical plane. Furthermore, the strength of the ac dipole can be increased by removing an additional 20 dB attenuator. The presented results offer a positive outlook to using the ac dipole and the extraction kicker for optics measurements at flat-top energy.

CONCLUSIONS

The overhaul of the LEIR BPM system saw first operation in 2022. Significant progress in the peak detection algorithm, as well as BPM phasing, has been made to achieve reliable transverse turn-by-turn data acquisitions.

All transverse beam excitation methods available in LEIR have been tested at flat-bottom energy. The transverse damper in ac dipole mode offers reliable coherent beam oscillations in both planes with sufficient amplitudes for optics measurements. Furthermore, the extraction kicker can be used at 13 kV to provide high amplitude horizontal kicks.

The first optics measurements of Run 3 have been performed at flat-bottom energy. Results have been obtained with both the ac dipole and extraction kicker. The results show a peak β-beating of 25% compared to the design model, which is within operational tolerance. A more realistic model that better represents the machine will need to be developed.

Lastly, optics measurements at flat-top energy are foreseen in 2023, using the ac dipole and extraction kicker as beam excitation methods. An extended stable flat-top period will be required to increase the number of available turns and provide a more stable measurement point in the cycle.

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REFERENCES

[1] J.Coupard *et al.*, "LHC Injectors Upgrade, Technical Design Report, Vol. 2 - Ions", CERN, Geneva, Switzerland, Rep. CERN-ACC-2016-0041, Apr. 2016.

[2] S. Albright, "Review of LEIR operation in 2018", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2020-0023, 2020.

[3] N. Biancacci *et al.*, "Linac3, LEIR and PS Performance with Ions in 2021 and Prospects for 2022", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1983–1986. doi:10.18429/JACoW-IPAC2022-WEPOPT055

[4] R. Alemany-Fernandez *et al.*, "Performance of the Low Energy Ion Ring at CERN with Lead Ions in 2022", presented at the IPAC'23, Venice, Italy, May 2023, paper TUPA151, this conference.

[5] G. Baud, O. Marqversen, and V. Kain, "Orbit and turn-by-turn system performances in 2018", LIU-Ions PS injectors Beam Dynamics Working Group, Mar. 2019, CERN, Geneva, Switzerland.

[6] N. Biancacci and V. Kain, "Analysis of turn by turn data acquired in 2018", LIU-Ions PS injectors Beam Dynamics Working Group, Oct. 2019, CERN, Geneva, Switzerland.

[7] F. Hoguin and S. Deghaye, "Solving the Synchronization Problem in Multi-Core Embedded Real-Time Systems", in *Proc. ICALEPCS'15*, Melbourne, Australia, Oct. 2015, pp. 942–946. doi:10.18429/JACoW-ICALEPCS2015-WEPGF102

[8] A. Schwinn *et al.*, "FESA3 – The New Front-End Software Framework at CERN and the FAIR Facility", in *Proc. PCaPAC'10*, Saskatoon, Canada, Oct. 2010, paper WECOAA03, pp. 22–26.

[9] F. Hoguin, S. Deghaye, R. Gorbonosov, J. Lauener, and P. Mantion, "Distributed Transactions in CERN's Accelerator Control System", in *Proc. ICALEPCS'21*, Shanghai, China, Oct. 2021, pp. 468–472. doi:10.18429/JACoW-ICALEPCS2021-TUPV033

[10] J. Borburgh, M. Crescenti, M. Hourican and T. Masson, "Design and construction of the LEIR extraction septum", CERN, Geneva, Switzerland, Rep. CERN-AB-2006-010-BT, 2005.

[11] J. Borburgh, M. Hourican, T. Masson and A. Prost, "The Septa for LEIR Extraction and PS Injection", CERN, Geneva, Switzerland, Rep. CERN-LHC-Project-Report-910, 2006.

[12] S. Peggs and C. Tang, "Nonlinear Diagnostics using an AC Dipole", Brookhaven National Laboratory, Upton, NY, Rep. RHIC/AP/159, 1998.

[13] R. Tomás, "Normal form of particle motion under the influence of an ac dipole", *Phys. Rev. ST Accel. Beams*, vol. 5, p. 054001, May 2002.

[14] R. Miyamoto, S.E. Kopp, A. Jansson and M.J. Syphers. Parametrization of the driven betatron oscillation. *Phys. Rev. ST Accel. Beams*, vol. 11, p. 084002, Aug. 2008.

[15] LEIR acc-models repository https://acc-models.web.cern.ch/acc-models/leir/